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Genesis of the Bauxitic Halii Soils

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FIGURE 1. A basalt boulder showing the unweathered rock core with the weathered portion of rock being a ferruginous bauxite. Ruler represents 2 feet.

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INTRODUCTION

Soils developed in moderately wet areas on the materials of the Koloa volcanic flows on the island of Kauai have a high content of gibbsite and iron oxide minerals. Gibbsite is present in saprolite beyond the lower limit of the soil solum. Thus, this ferruginous gibbsitic material is the parent material of the soil. In this subsurface zone the rocks retain their original physical structure even though weathered completely to sesquioxides. These weathered rocks have a hard outer crust and also a hard interior when dry. In their normal wet or moist condition they can be easily cut by a knife.

The soils contain aggregates, plinthite, which is made up of hardened gibbsite and iron oxides. At the upper surface of the soil these aggregates have become hardened with a shiny coat of hematite. This coating process may take place through the migration of iron oxide from the interior of the aggregate to its surface during periods of wetness and subsequent precipitation and dehydration of the iron oxide during dry periods; by deposition of iron oxide from percolating water on the surface of peds of weathered rock; or by removal of gibbsite and accumulation of iron in place.

The nature of the parent ferruginous bauxitic weathering material is of even greater interest. It is the first product of weathering of the ultrabasic rocks such as melilite-nepheline basalt, nepheline basalt, melilite basalt, and basanite, the original rocks of the Koloa volcanic series in this area. The great intensity of the chemical weathering which transforms the fresh rock to parent material in a weathering zone of less than 0.1 inch is due to the high rainfall with relatively uniform distribution and to facilities for the rapid drainage of percolating free water in the weathering zone. This sharp boundary is illustrated in figure 1, which shows the hardened outer surface of the original boulder and a fresh unweathered core of the basalt. A fine-textured weathered material occurs between the hardened surface layer and the unweathered rock core. As depicted in the illustration, this material has a sharp contact zone to the unweathered rock core. Inasmuch as the intense chemical weathering has taken place *in situ,* this weathered material can be considered the first product of weathering. The boulder (figure 1) offered an excellent opportunity to study the nature of the mineral decomposition of the original rock and the type of secondary mineral formation. The high content of gibbsite and iron oxides in these materials would indicate that conditions for resilication described by Alexander *et al.* (1942) do not exist in this weathering situation.

The weathered boulder shown in figure 1 was found in 1956, during a soil correlation study of the soils occurring on the Koloa volcanic flows on Kauai, in a plantation road cut near the water reservoir in the old Wailua Game Refuge Area. The soils of this area have been classified by Cline *et al.* (1955) as the Halii soil series of the Honolua family of the Humic Latosol great soil group. In this correlation study of 1956 they were tentatively reclassified to the Halii family of the Aluminous Ferruginous Latosol great soil group. A number of boulders were cut open before this boulder with an unweathered core was discovered. As a result of this discovery a two-phase study was initiated: the first, to determine the mineral and chemical composition of the weathered material existing in the cross sections exposed by cutting across weathered boulders; the second, to study the properties and characteristics of three Halii soil profiles which had developed on this type of weathered parent material.

EXPERIMENTAL METHODS

Rock Weathering

Samples were collected in 1956 to represent a horizontal cross section of the weathered boulder with the unweathered core shown in figure 1. Each sample was taken in a 1- to 2-inch section to conform with apparent physical changes in the materials found in the rock. Another completely weathered rock was sampled in a similar manner. These samples were taken for chemical analysis and were analyzed by methods described by Piper (1944) for the determination of oxides.

In 1957 the weathered rock with the unweathered core was again sampled for mineralogical analysis of the composition and the character of the mineral occurrence. These were determined by differential thermal analysis, X-ray diffraction, and petrographic microscope study of thin sections. The 1957 samples were also analyzed for certain elements by X-ray fluorescence techniques.

Halii Soil Profiles

For this intensive study of their soil genesis, three typical soil profiles of the Halii series were selected on the slopes of Kilohana Crater on Kauai. Each profile was described by horizon and sampled. The samples were analyzed for chemical and mineral composition by the same procedure used for samples taken for the rock-weathering studies. In addition, cation exchange capacity and exchangeable cations were determined by procedures described by Piper (1944), except that exchangeable manganese and ferrous iron were determined by methods described by Jackson (1958), and exchangeable aluminum by methods proposed by Chenery (1948).

The soils were subject to certain physical studies. The degree of magnetism was determined in the field by hand magnet. Bulk density measurements were made by the method described by Wright (1939). The samples contained nodules and concretions larger than 2 millimeters. These were separated by a standard sieve and the separate portions were weighed. Each of these samples was subject to chemical analysis.

The descriptions of the three profiles and their locations, by William M. Johnson, Soil Survey, Soil Conservation Service, United States Department of Agriculture, are as follows:

I. SAMPLES OF WEATHERING BASALT

Location: 1¼ miles northwest of Puu Pilo in the Wailua Game Reserve Area of Kauai, State of Hawaii.

Elevation: 440 feet.

Rainfall: About 110 inches per year.

Notes: The boulder sampled was partially exposed in a field road-cut. Apparently it lay about 3 or 4 feet below the original soil surface. Road construction has mutilated the overlying soil profile so that it is unsuitable for samples. All of the surrounding area has soils of the Halii series. The basalt in this area has been identified by geologists as an ultrabasic type of basalt and classified as part of the Koloa Flow. At the time of sampling the material was dry, except for the interior of the hard core which exuded water when pieces were chipped off. Samples taken from hard core upward.

Description

2-1-1.* Chips of the hard rock core. Dark bluish-gray (10B 4/1, dry; nearly black, 2/1, moist)† extremely hard basalt. In hardness and toughness it is like fresh, unweathered basalt. Fine-grained, with common vesicles from ¼ to 2 mm. in diameter. The rock contains numerous pale-green crystals that look like olivine. The rock is strongly magnetic. There is evidence (mainly in rusty stains and whitish areas) that at least the outer 1 inch of the rock has undergone some weathering. Extremely abrupt boundary with the soft weathering shell that surrounds this hard core.

2-1-2. An undisturbed core of the weathering shell from the upper surface of the hard core, outward a distance of 4 inches. Strong-brown (7.5YR 5/6, dry; 4/5, moist), massive, clayey material. Hard when dry; friable when moist; nonplastic and nonsticky when wet. Few very fine white and pale-yellow flecks (dry). Porosity and pattern of very fine mottles suggest appearance of original basalt. Moderately magnetic. Abrupt boundary with overlying weathering shell.

2-1-3. Loose pieces of the hardened shell, 4 to 5 inches from the upper surface of the hard core. This is a hardened, massive, concentric shell. Orientation of the fragments is easily determined by their convexity. Brown (7.5YR 4.5/4, dry), dark reddish-brown (5YR 3/4) when moist, with few fine white flecks and very few fine red specks. Extremely hard when dry; does not soften upon moistening. Has porosity and fine mottling suggestive of original basalt. Moderately magnetic. Abrupt boundary with overlying weathering shell.

* Sample number.
† Munsell soil colors.

2-1-4. Loose pieces of the hardened shell, 5 to 6½ inches from the upper surface of the hard core. This, like the preceding sample, is of hardened, massive material in a concentric shell. Convexity of the fragments indicates their orientation. Strong brown (7.5YR 5/6, dry), dark reddish-brown (5YR 3/4) when moist, with few very fine white flecks. Extremely hard when dry and does not soften upon moistening. Porosity and fine mottling suggest appearance of original basalt. Moderately magnetic. Abrupt boundary with overlying weathering shell.

2-1-5. Loose pieces of the hardened shell, 6½ to 7½ inches from the upper surface of the hard core. This, too, is from hardened, massive, concentric shell. Orientation of the fragments is indicated by their convexity. Brown (7.5YR 5/4, dry), reddish-brown (5YR 4/3) when moist, with common very fine white and dark-red flecks. Extremely hard when dry and does not soften upon moistening. Pores and fine mottling pattern suggest the original basalt. Moderately to strongly magnetic. This is the outermost concentric weathering shell. It has an abrupt boundary with the surrounding friable, earthy material.

Since this description was made nontronite has been found in cavities in the rock surface and in hard, resistant areas in the outer weathered portion of this rock. Nontronite was found as a pore filling in one area of the weathered portion of the rock. Evidence of decomposition products of nontronite was found, indicating the following sequence: nontronite → various decomposition products of nontronite → iron oxide.

II. HALII GRAVELLY CLAY

Location: Deep pit dug for an aluminum mining company. On northwest slope of Kilohana Crater, Kauai, State of Hawaii. About 22° 30″ N. Lat., 159° 26′ W. Long.

Elevation: 880 feet.

Rainfall: Estimated about 100 inches per year.

Topography: Northwest-facing slope of Kilohana Crater. Slope about 6 percent, slightly convex. Rather smooth, sloping surface that is little dissected by erosion.

Drainage: Well drained. Runoff medium. Permeability moderate.

Vegetation: Mainly a thicket of *Melastoma* bushes 6 to 10 feet high. There is a little lantana, yellow foxtail, and ricegrass, especially along trails and other places where the *Melastoma* is sparse.

Parent Material: Ferruginous bauxite, derived from the weathering of basalt, probably with admixture of cinders and ash. Also suspect some ash deposition at the surface some time after soil began to form. The conspicuously horizontally banded substratum suggests pseudostratification of the original basalt-cinder material from Kilohana Crater.

Notes: The pit was dug to a depth of 22 feet, but had been partially filled by the time our party had opportunity to examine it. According to laborers who sampled the pit for the aluminum mining company, visible evidence of aluminum ore (gibbsite) decreased markedly below a depth of 17 feet. The entire profile was very moist at the time samples were taken. The description below was taken from samples. The parent material (rock, etc.) has been identified as part of the Koloa Flow.

Profile

2-2-1. A_{12}(?) 0–5 inches Dark reddish-brown (5YR 3/2, dry; 2/2, moist) clay that feels like heavy silty clay loam in the fingers. Has common fine and medium mottles of brownish-yellow (10YR 6/6, dry) due to small aggregates of

			some hard mineral, probably gibbsite. These aggregates range in size from about 1/4 to about 15 mm. in diameter. Moderate coarse and medium granular structure. Hard when dry; plastic and slightly sticky when wet. Has common pores from 1/2 to 2 mm. in diameter. Many roots. All the material except the yellowish hard aggregates is strongly magnetic. This probably represents the second horizon of the profile. The soil surface was badly disturbed during excavation, and no attempt was made to identify and sample the uppermost horizon. Clear, slightly wavy lower boundary.
2-2-2. (6″–11″)	B_{21}(?)	5–18 inches	Indistinctly mottled dark reddish-brown and reddish-brown (5YR 3/4 and 4/4, dry), with few fine and medium brownish-yellow flecks, probably due to gibbsite aggregates; mottled dark reddish-brown (5YR 2/3 and 3/3) when moist. Clay that feels like heavy silty clay loam in the hand. Moderately medium and fine subangular blocky structure. There are common small patches on vertical and horizontal surfaces that suggest clay skins. Hard when dry; friable when moist; plastic and sticky when wet. Few fine pores, from 1/2 to 1 mm. in diameter. All the material is moderately magnetic (less so than in overlying horizon). Common fine roots; roots do not penetrate deeper than base of this horizon, except perhaps in places where there are cracks or fissures in the underlying horizon. Under polarized light, all the fine material in this horizon appears to be either crystalline or opaque. Abrupt, smooth lower boundary.
2-2-3.	B_{22}(?)	18–20 inches	Finely, distinctly mottled red, yellowish-red, and dark brown (2.5YR 4/6, 5YR 5/8, and 7.5YR 3/2, dry), becoming mottled dark red, red, and dark reddish-brown (2.5YR 3/6, 2.5YR 4/8, and 5YR 2/2) when moist. Massive, indurated material that appears to be hardened, weathered basalt. Suspect that it has been recharged with iron oxide precipitated out of soil solution. The material has structure and porosity like that of basalt. All of the material is moderately magnetic. Abrupt, smooth lower boundary.
2-2-4. (21″–26″)	C_1(?)	20–30 inches	Dark reddish-brown (5YR 3/2, dry) with common, fine, distinct mottles of reddish-yellow (7.5YR 6/8, dry); becoming dark reddish-brown (5YR 2/2) mottled with strong brown (7.5YR 4/6) when moist. Clay that feels like silty clay loam in the hand. Moderate medium subangular blocky, breaking to fine and then to very fine subangular blocky structure. Slightly hard when dry; friable when moist; plastic and sticky when wet. Common fine pores, 1/2 to 1 mm. in diameter. Very few patches on horizontal surfaces that suggest clay skins. All of the material is strongly magnetic. Gradual lower boundary.
	C_2, etc.	30–180 inches +	This substratum consists of horizontally banded material varying in color and in content of hard and soft plinthite (laterite) fragments. Core samples were taken to represent the range in materials, as follows:
2-2-5.	C_2	40–43 inches	Brown (7.5YR 4.5/1.5, dry) with common, medium and fine, distinct mottles of dark reddish-brown (5YR

			3.5/4, dry); dark brown (7.5YR 2.5/2, moist) mottled with dark reddish-brown (5YR 3/4, moist). Appears to be incompletely weathered, hard basalt. Massive; indurated or extremely hard—cannot be broken in the hand. Porosity and fracture are like basalt. Mottles are pore fillings and linings. There is a reddish-brown clayey coating on the upper horizontal surface that appears to consist of clay skins. All the material is strongly magnetic.
2-2-6.	C_3	72–74 inches	Brown (7.5YR 4/2, dry) with common fine and medium mottles of reddish-yellow (7.5YR 6/8, dry); becomes dark reddish-brown (5YR 3/4) mottled with darker reddish-brown (5YR 2.5/3) when moistened. This is mainly weathered basalt that is hard to extremely hard, with a little clayey matrix. Most of the material has basalt fracture and porosity. No clay skins observed. All material is strongly magnetic. Very slight effervescence with hydrogen peroxide.
2-2-7.	C_4	80–85 inches	Dark reddish-brown (5YR 3.5/3, dry) with common, distinct, very fine specks of reddish-yellow (dry); becomes somewhat duller colored (5YR 3/2) when moistened. Clay that feels like silty clay loam in the hand. Weak medium and fine subangular blocky structure. Soft when dry; very friable when moist; plastic and slightly sticky when wet. Common very fine pores, ¼ to 1 mm. in diameter. The reddish-yellow flecks are very hard and are probably gibbsite aggregates. There are common patches on vertical and horizontal surfaces that look like clay skins. Very slightly effervescent with hydrogen peroxide. All the material is strongly magnetic.
2-2-8.	C_5	125–130 inches	Finely, faintly mottled dark reddish-brown and reddish-brown (5YR 3/3 and 4/4, dry) with few very fine white specks; faintly mottled dark reddish-brown (5YR 3/3 and 3/4, moist) with white and very pale-brown flecks. Clay that feels like silty clay loam in the hand. Massive. Soft when dry; very friable when moist; plastic and sticky when wet. Common very fine pores, ¼ to 1 mm. in diameter. There are patches along vertical surfaces that look like clay skins. All the material is strongly magnetic.
2-2-9.	C_6	158–163 inches	Reddish-gray (5YR 5/2, dry) with common medium and fine mottles of white, yellow, very pale brown, and black; becomes dark reddish-brown (5YR 3.5/2) mottled as above, when moistened. Clay that feels like silty clay loam in the hand. Massive. Slightly hard when dry; friable when moist; plastic and slightly sticky when wet. No clay skins seen. Strongly magnetic. Has appearance of weathered basalt.

III. HALII GRAVELLY CLAY

Location: Pit dug on northern slope of Kilohana Crater, Kauai, State of Hawaii. About 22° 0′ 18″ N. Lat., 159° 25′ 51″ W. Long.

Elevation: 940 feet.

Rainfall: Estimated about 100 inches per year.

Topography: Smooth, uniform northern slope of Kilohana Crater, only a short distance from the top of the volcano. Slope about 10 percent, gently convex.

Drainage: Well drained. Little runoff except during heavy rain, when runoff is probably medium. Permeability moderate.

Vegetation: Thick, almost pure stand of *Melastoma* shrubs, 6 to 10 feet high. Around clearings and along roads there is a little lantana, yellow foxtail, and ricegrass. Earth's surface is barren of understory beneath the thick *Melastoma* stands.

Parent Material: Ferruginous bauxite, derived from weathering of basalt, probably with admixture of cinders and ash. Also suspect some ash deposition at the surface some time after soil began to form. The conspicuous horizontal color bands, and horizontal layering of hard materials in the substratum suggest a layered cinder-lava deposit.

Notes: It seems likely that there was forest cover on the soil in the past. In *Melastoma* thickets nearby one finds an occasional large silver oak and scattered ohia trees; also, there are burnt stumps of some large trees. The lava in this vicinity has been identified by geologists as part of the Koloa Flow. The entire profile was moist when described and sampled. From all external appearances, it is a virgin profile.

Profile

2-3-1.	A_{11}	0–3 inches	Dark grayish-brown (10YR 4/2, moist) gravel and very coarse sand, containing a little clay. Loose. Matted with grass roots. Much discrete particles of organic matter. Effervesces very weakly with hydrogen peroxide. The pebbles and sand grains are of the kind usually called ironstone. The larger ones (and some of the small ones) are porous, with mottled interiors and with soft, earthy centers. Some of the smaller ones are dense, nearly nonporous, and extremely hard throughout. The outermost 1 mm. or so of all pebbles and sand grains appears denser, more brittle, and harder than the interiors. Pebbles are irregularly rounded. It seems likely that all have formed by hardening of bits of plinthite. 80 to 90 percent of the pebbles and grains are magnetic. Abrupt, smooth lower boundary.
2-3-2.	A_{12}	3–6 inches	Very dark grayish-brown (10YR 3.5/3, moist) sandy, gravelly clay. Strong very fine subangular blocky structure; peds 1 to 5 mm. in diameter. Friable when moist; plastic and sticky when wet. Matted with roots. Pebbles and sand grains as described in A_{11}. Most of them magnetic. Very weak effervescence occurs with hydrogen peroxide. Clear, smooth lower boundary.
2-3-3.	B_{21}	6–15 inches	Strong-brown (7.5YR 4/5, moist) clay that feels like heavy silty clay loam in the hand. Moderate medium subangular blocky, breaking to weak fine and very fine subangular blocky structure. Friable, very plastic, sticky. Contains numerous hard and soft pebbles, from 1 mm. to several centimeters in diameter; all of these appear to be fragments of plinthite and gibbsite. Common roots. Common pores, less than ½ mm. in diameter. There are numerous patches, almost continuous coatings around peds, of what look like clay skins. Much of the material, including the earthy part, is magnetic. Abrupt, slightly wavy lower boundary.

2-3-4.	B_{22}(?)	15–18 inches	Dark reddish-brown (5YR 3.5/4, moist) gritty clay that feels like gritty silty clay. Moderate medium subangular blocky, breaking to moderate fine and very fine subangular blocky structure. Friable when moist; very plastic, very sticky when wet. In places the material is massive, apparently cemented with something; these parts are extremely firm; they cannot be broken in the hand. Common pores, ½ to 2 mm. in diameter that look like worm holes. Few roots. No effervescence with hydrogen peroxide. Almost all of the material is strongly magnetic. There are numerous patches, nearly continuous in places, of what look like clay skins. Abrupt, slightly wavy lower boundary.
2-3-5.	B_{31}(?)	18–24 inches	Dark reddish-brown (5YR 3/2, moist) gritty clay that feels like clay loam in the hand. Weak coarse and medium subangular blocky structure. Friable when moist; plastic and sticky when wet. Has common, fine, distinct mottles of strong brown; these are caused by extremely hard aggregates suspected to be gibbsite. In addition, there are small and large, soft and hard pieces of plinthite scattered throughout the horizon. Very few, very fine roots. No effervescence with hydrogen peroxide. Common patches of what look like clay skins on all surfaces and in pores. These patches seem to dry darker rather than lighter in color, suggesting that they may be only areas of allophanic material rather than real clay skins. Abrupt, wavy lower boundary.
2-3-6.	B_{32}(?)	24–26 inches	Red (2.5YR 4/6, moist) clay that feels like gritty clay loam. Weak coarse subangular blocky structure. Friable when moist; plastic and sticky when wet. In many places the material is massive and extremely firm, as if cemented with something. Very few, very fine roots. Common pores, ½ to 4 mm. in diameter. No effervescence with hydrogen peroxide. Most of the material is strongly magnetic. Numerous patches of what appear to be clay skins; almost continuous in places. Abrupt, wavy lower boundary.
2-3-7.	C_1(?)	26–31 inches	Dark brown (7.5YR 3/2, moist) with common, fine, distinct mottles of strong brown, especially in a 1½-inch-thick band running through the center of the horizon. Below this center band the soil is slightly redder in hue. Clay that feels like clay loam. Weak coarse subangular blocky structure. Friable when moist; plastic and sticky when wet. The strong-brown mottles are due to extremely hard aggregates that are suspected to be gibbsite. No effervescence with hydrogen peroxide. All of the material is strongly magnetic. There are what appear to be common thin patches of clay skins on all surfaces. Common pores, ½ to 4 mm. in diameter. Very few, very fine roots. As in the horizons above, the material contains soft and hard plinthite fragments, ¼ to several inches in diameter, that have the appearance of weathered basalt. Abrupt, wavy lower boundary.
2-3-8.	C_2(?)	31–52 inches	This consists of 3 red layers, each rather thin, with interlayered dark-brown horizons (or strata?), like the sequence described above. The frequency of plinthite

			fragments appears to increase with increasing depth. 95 to 98 percent of the material is strongly magnetic. There are few to common patches of what look like clay skins.
2-3-9.	C_3(?)	52–80 inches	This consists of 3 more pairs of red and dark-brown layers as described above. The material seems to persist about as plastic and sticky as in the sequences above. No roots observed below 54 inches. Most of the material, although friable, has the appearance (porosity and mottling) of the supposedly original basalt. There are common thin patches of what look like clay skins. All of the material is strongly magnetic.
2-3-10.	C_4(?)	80–85 inches	Dark reddish-brown (5YR 3/3, moist) with common, medium and fine, distinct mottles of reddish-yellow that may be due to gibbsite aggregates. Clay that feels like clay loam. Massive. Soft, very friable, slightly plastic, nonsticky. Common very fine pores, ¼ to 1 mm. in diameter. There are a few patches of what looks like clay skins. All of the material is strongly magnetic.

IV. HALII GRAVELLY CLAY

Location: Pit on southwest slope of Kilohana Crater, Kauai, State of Hawaii. Just to east of unsurfaced road leading to top of crater. About 22° 59′ 40″ N. Lat., 159° 26′ 10″ W. Long.

Elevation: 860 feet.

Rainfall: Estimated about 100 inches per year, possibly a little more.

Topography: Smooth slope near crest of Kilohana Crater. Slope about 5 percent, convex, facing toward the southwest.

Drainage: Well drained. Runoff slight to none except during heavy showers, when it is probably medium. Permeability above and below the iron pan is moderate. Permeability in iron pan is zero.

Vegetation: Thick cover of *Melastoma* shrubs, lantana, ricegrass, glenwood grass, yellow foxtail, strawberry guava, Boston fern, mountain orchid, a low-growing mimosa, and silver oak. It is possible that the soil supported a forest cover at one time.

Parent Material: Ferruginous bauxite derived from weathering of basalt, probably with admixture of cinders and ash. Also suspect some ash deposition at the surface some time after the soil began to form. Substratum has conspicuous horizontal color bands noted in other profiles of Halii. The lava here has been identified by geologists as part of the Koloa Flow.

Notes: Besides bulk samples and, where possible, undisturbed cores in cans, cores were taken of material in the different horizons for bulk density determinations. The entire profile was moist or very moist when described and sampled.

Profile

2-4-1.	A_{11}	0–3 inches	Dark-brown (7.5YR 3/4, moist) sandy and gravelly clay that feels like sandy and gravelly silty clay loam. Strong medium granular structure. Very hard when dry; firm when moist; plastic and sticky when wet.

			Matted with roots. Very porous. A small proportion (10 to 20 percent) of the material is moderately magnetic. Sand and gravel consist of rounded ironstone; most pebbles and grains appear to have porosity and general appearance of weathered basalt, and are probably hardened plinthite. Clear, wavy lower boundary.
2-4-2.	A_{12}(?)	3–8 inches	Dark-brown (10YR 4/3, moist) coarse sand and gravel with a little clay. Sand and gravel are ironstone fragments that have porosity and general appearance of weathered basalt; they are probably hardened plinthite fragments. Pebbles and grains have a thin white "frosting" of minute whitish grains so that dried surfaces have color of about 10YR 6/2 (light brownish-gray). Loose or only slightly coherent. Many roots. Very porous. 25 to 50 percent of the material is moderately magnetic. Clear, wavy lower boundary.
2-4-3.	B_{21}(?)	8–10 inches	Dark brown (7.5YR 4/3, moist) with common, distinct, fine and medium mottles of yellowish-red (5YR 4/6, moist). Coarse sandy clay that feels like sandy clay loam in the hand. Moderate very fine subangular blocky structure. Friable when moist; plastic and sticky when wet. Sand grains consist of rounded ironstone pellets; there are also small plates of discontinuous ironstone seams. Common fine roots. Numerous pores, ½ to 2 mm. in diameter. Under a microscope, the pebbles and grains appear to have a thin "frosting" of white grains, about silt size, as in horizon above. There are common patches of what appear to be clay skins. 25 to 50 percent of the material is moderately magnetic. Water seeps slowly out of this horizon in the pit. Abrupt, wavy lower boundary.
2-4-4.	B_{22}	10–19 inches	Faintly mottled reddish-brown and dark reddish-brown (5YR 4/4, 5YR 3/3, and 2.5YR 3/4, all moist) hard plinthite. Upper surface of this horizon has a nearly black, indurated iron oxide (?) cap from 1 to 3 mm. thick. In cracks between the large plinthite fragments is clay that is brown in color (7.5YR 4.5/4, moist); this clay feels like silty clay loam in the hand; it appears to have been washed down from horizon above. The only roots that get through this horizon are those that find the cracks in the hard material. Water seeps out of these cracks. More than 50 percent of the material in this horizon is moderately magnetic. Abrupt, wavy lower boundary.
2-4-5.	B_{23}(?)	19–31 inches	Coarsely mottled dark reddish-brown and dark-brown (6YR 3/4 and 7.5YR 3/2, both moist) clay that feels like gritty clay loam in the hand. Moderate medium subangular blocky structure. Friable when moist; plastic and sticky when wet. There are some areas in this horizon that feel like heavy silty clay loam in the hand; these patches are firm when moist; very plastic when wet. Contains numerous pieces of hard and semihard plinthite, ½ to 6 inches in diameter. Few fine roots. Appears to have thick, nearly continuous clay skins on all surfaces and in pores. More than 50 percent of the material is moderately magnetic. Abrupt, wavy lower boundary.

2-4-6.	B_3(?)	31–33 inches	Dark red (2.5YR 3/6, moist) with common, faint, fine mottles of reddish-brown and pore linings of brown. Clay that feels like silty clay loam in the hand. Moderate coarse subangular blocky structure. Friable when moist; plastic and sticky when wet. Contains common hard plinthite fragments from ½ to 2 inches in diameter. Numerous pores ½ to 2 mm. in diameter. Few fine roots. Has what appears to be moderate, nearly continuous clay skins on all surfaces and in pores. About 50 percent of the material is moderately magnetic. Abrupt, wavy lower boundary.
2-4-7.	C_1(?)	33–42 inches	Dark reddish-brown (5YR 3/3 in upper part, changing to 5YR 3/4 in lower part, moist) with common, distinct, medium and fine mottles of yellowish-brown and red (moist). Clay that feels like gritty clay loam in the hand. Massive. Friable when moist; plastic and sticky when wet. Red-mottled areas seem to be less sticky than reddish-brown ones. Contains numerous hard and semihard plinthite fragments ½ to 3 inches in diameter, that retain appearance of weathered basalt. Numerous pores, ½ to 4 mm. in diameter. Very few fine roots. Has what appears to be very numerous patches of moderately thick clay skins on all surfaces and in pores. All the material is strongly magnetic. Clear, wavy lower boundary.
2-4-8.	C_2(?)	42–54 inches	Yellowish-red (5YR 4/6, moist) with common, distinct, medium and fine mottles of dark reddish-brown and few fine mottles of reddish-yellow. Hard and semihard plinthite that retains appearance of original basalt. Cracks between plinthite fragments have filled with clay that feels like heavy silty clay loam in the hand. The clay is friable when moist; plastic and sticky when wet; has numerous fine pores. Some vesicles of the plinthite fragments have linings and fillings of white opaque material. Appears to have patchy, thin to moderately thick, clay skins; they are mainly red in color, but some are reddish-brown or reddish-yellow. More than 50 percent of the material is moderately magnetic. Clear, wavy lower boundary.
2-4-9.	C_3(?)	54–66 inches	Coarsely, distinctly mottled dark reddish-brown, yellowish-red, and red (5YR 3/3, 5YR 3/4, 5YR 3/6, and 2.5YR 4/8, all moist) clay that feels like gritty clay loam in the hand. Massive. Friable when moist; plastic and sticky when wet. Common fragments of hard and soft plinthite, ½ to 5 inches in diameter. Very few, very fine roots. Numerous fine pores ½ to 4 mm. in diameter. Appears to have common thin to moderately thick patchy clay skins on all surfaces and in pores. All the material is strongly magnetic.

RESULTS OF STUDIES OF WEATHERING OF ROCKS

Weathered Rock with Unweathered Core

The results of the chemical analysis of the weathered rock shown in figure 1 are given in table 1. The samples were taken on a horizontal cross section across the rock as shown in figure 1. The data show a tremendous and rapid desilication of the weathered material has occurred from the center outward as the silica has decreased from 36.7 percent in the weathered core to 2.0 and 2.4 percent in samples of weathered material in contact with it. There is some evidence of weathering in the outer portion of the rock, but the change is abrupt at the point of contact between rock and saprolite in contact with it, as illustrated in figure 1.

TABLE 1. Chemical composition of samples taken from rock core to outer surface of the weathering melilite-nepheline basalt shown in figure 1

LOCATION OF SAMPLE IN ROCK		SiO_2, PERCENT	Al_2O_3, PERCENT	Fe_2O_3, PERCENT	TiO_2, PERCENT	WATER LOSS 110°–400° C., PERCENT
Rock core melilite-nepheline basalt		36.7	10.8	14.2	2.8	—
Weathered material	(a)	2.0	39.3	37.0	5.5	16.3
next to rock core........	(b)	2.4	39.3	36.5	6.6	16.8
Weathered material 1½–3 inches from rock	(a)	2.1	41.2	36.1	5.0	16.8
core	(b)	1.9	43.1	36.6	5.8	16.7
Weathered material 3–5 inches from rock	(a)	5.5	46.3	28.7	3.6	17.9
core	(b)	4.4	45.8	28.0	4.1	17.7
Weathered outer surface 5–7 inches	(a)	4.0	48.5	26.0	3.1	17.3
from rock core..........	(b)	4.7	47.0	25.1	3.3	17.5

The chemical composition of the samples from the weathered portion of the cross-sectional sampling shows the following relationships: *silica* (SiO_2) content increased from 2.0 and 2.4 percent in the samples on contact with rock to 4.0 and 4.7 percent in the harder outer shell of the weathered boulder; *aluminum oxide* (Al_2O_3) content increased in same samples from 39.3 percent to 48.5 and 47.0 percent; *iron oxide* (Fe_2O_3) content decreased gradually from 37.0 and 36.5 percent in sample adjacent to rock, to 26.0 and 25.1 percent in the outer crust; *titanium oxide* (TiO_2) content decreased in the same manner from 5.5 and 6.6 percent to 3.1 and 3.3 percent; and, there was a slight increase in *water* loss between 110° C. and 400° C. The data indicate a progressive loss of titanium oxide and iron oxide after the rapid desilication of the rock.

Table 2 reports the content of zirconium oxide, chromium oxide, titanium oxide, and manganese oxide as determined by X-ray fluorescence analysis in samples collected in vertical cross section from rock core to outer crust. The content of zirconium oxide (ZrO_2) was almost twice as high in the weathered fraction as it was in the rock, 0.025 and 0.013 percent, respectively. The chromium oxide (CrO_2) content increased from 0.08 percent in the rock to more than 0.2 percent in the weathered bauxitic material. The titanium oxide content, following the same trend as it did in table 1, increased about threefold in the weathered material in contact with the rock, 2.2 to 6.5 percent, and then decreased gradually to 3.9 percent in the outer crust. Manganese oxide (MnO) content was much lower in the weathered bauxitic material than in the rock core, 0.20 percent decreasing to less than 0.06 percent.

The data presented in figure 2 were obtained from the differential thermal analysis of the cross-sectional samples reported in table 1. The data show a strong endothermic reaction between 350° C. and 360° C., which is characteristic of gibbsite, and of some of the iron oxide minerals. This endothermic reaction in-

TABLE 2. Estimated amounts of zirconium, chromium, titanium, and manganese by X-ray fluorescence analysis in rock and soil samples, Kauai, Hawaiian Islands

	PERCENT			
SAMPLE NO.	ZrO_2	Cr_2O_3	TiO_2	MnO
2-1-1	0.013	0.08	2.2	0.203
2-1-2	.025	.26	6.5	.058
2-1-3	.021	.20	4.7	.058
2-1-4	.022	.20	4.8	.044
2-1-5	.017	.22	3.9	.036
2-2-3 (Porous Brown)	.014	.12	3.5	.058
2-2-3	.014	.18	4.3	.073
2-2-5	.017	.18	1.5	.080
2-2-6	.012	.10	3.7	.109
2-3-1	.009	.30	5.4	.036
2-3-2	.014	.34	6.5	.029
2-3-3	.022	.30	8.9	.036
2-3-4	.022	.28	7.8	.044
2-4-1	.020	.38	7.4	.051
2-4-2	.010	.26	3.9	.007
2-4-3	.021	.32	8.2	.029
2-4-4	.022	.28	4.8	.044
2-4-8	.016	.26	4.8	.044
2-4-9	.023	.26	9.7	.073

creases, as one progresses through the samples from that in contact with the rock to the outer crust. From the differential thermal analysis of the samples shown in figure 2, the gibbsite content is estimated to be 60 to 73 percent. Goethite was identified either by X-ray diffraction or by optical examination of thin sections as pseudomorphs after olivine. The strongly magnetic properties of these samples indicate the presence of magnetite or maghemite. Some evidence of gibbsite in the rock core is indicated by the small endothermic reaction above 300° C. in the curve for the rock core. The small endothermic reaction at 570° C., shown in curves of samples from the outer crust, is due to kaolin minerals, probably halloysite.

The data given in table 3 were obtained from the chemical analysis of samples taken on a cross-sectional line across a completely weathered boulder. In general, the analysis follows the same changes in chemical composition found in the analysis given in table 1. The weathering of this boulder is featured by more nearly com-

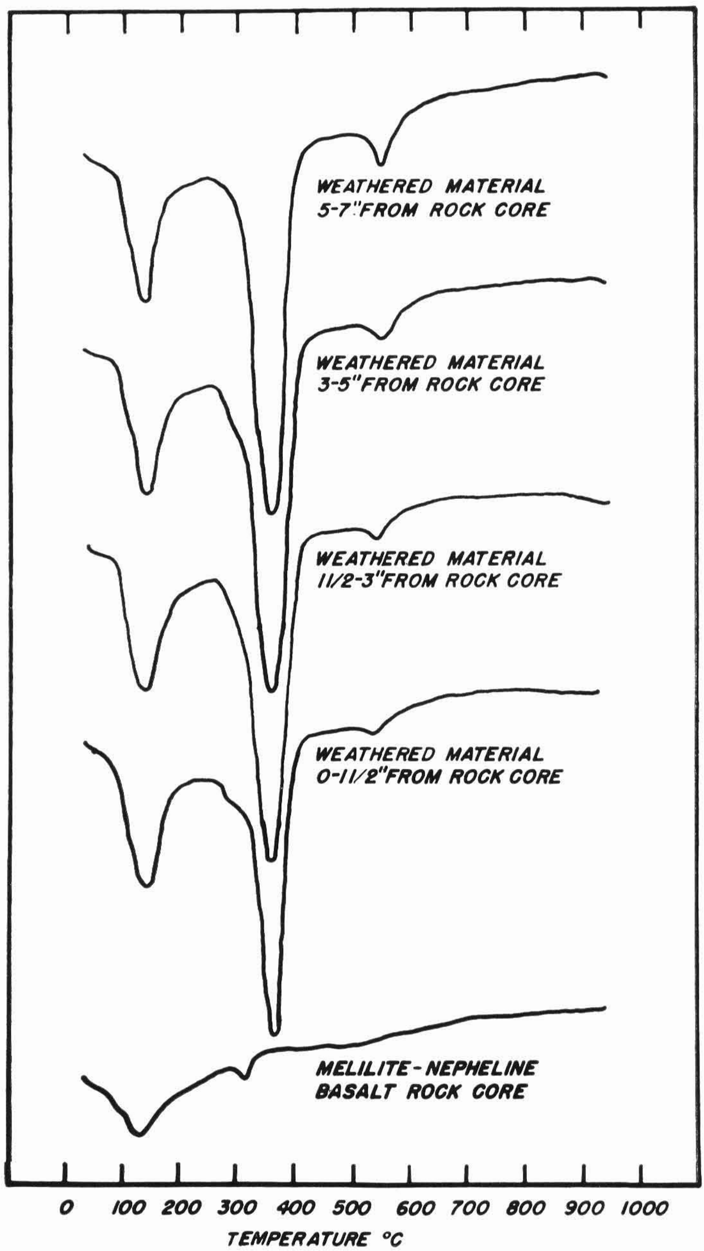


FIGURE 2. Differential thermal analysis of weathered melilite-nepheline basalt rock. Left endothermic peak indicates adsorbed water, second peak indicates hydrated sesquioxides, and the third weak peak indicates kaolin.

plete desilication as evidenced by the extremely low silica content outside of the center of the boulder. The *silica* content was found to be 2.1 percent in the center of the boulder and then it decreased to a mere trace in weathered material toward the outer edge of the boulder, and the outer surface layer had a silica content of only 0.4 percent. The other relationships in chemical composition are as follows: *aluminum oxide* content ranged from 19.2 percent in the center to 36.2 percent near the center and to more than 40 percent in the outer portion of the boulder; *iron oxide* content was 60.8 percent in the center, and then dropped rapidly to its lowest level at the outer surface of the boulder where it was 32.5 percent; the *titanium oxide* content decreased from 5.5 percent in the center to 4.1 percent at

TABLE 3. Chemical composition of samples taken progressively from the center to outer surface of a completely weathered melilite-nepheline basalt

LOCATION OF SAMPLE IN WEATHERED BOULDER	SiO_2, PERCENT	Al_2O_3, PERCENT	Fe_2O_3, PERCENT	TiO_2, PERCENT	WATER LOSS 110°–400° C., PERCENT
Center of boulder	2.1	19.2	60.8	5.5	14.1
2 inches from center	0.0	36.2	38.6	6.0	16.8
4 inches from center	0.0	44.0	29.9	4.8	20.9
Outer crust 4 to 6 inches	0.4	41.7	32.5	4.1	18.9

the outer surface of the boulder; and the *water* loss between 110° C. and 400° C. ranged from 14.1 percent in the center of the boulder to 20.9 percent near the outer layer.

The results of the differential thermal analysis of the completely weathered boulder reported in table 3 are given in figure 3. The strong endothermic reaction between 350° C. and 360° C. is due to the presence of gibbsite. The curves show a high content of gibbsite in all samples except the core samples, which on chemical analysis showed a very high iron oxide content.

Samples were collected from the rock and weathered portion of the boulder shown in figure 1 for mineralogical analysis, using thin sections. The data obtained from the examination of these thin sections by the use of petrographic microscope are as follows:

Unweathered Rock

The outer edge of approximately an inch showed evidence of weathering in that some of the pores had small beads of translucent crystalline material which were identified as nontronite. The scattered crystals of olivine were decomposing to ferruginous-appearing materials. In pockets of the outer surface of the boulder the smoothly surfaced well-defined aggregates of crystalline nontronite occurred in clusters.

In the inner portion of the rock the dominant mineral components were as follows: *olivine*—largest phenocrysts occurred generally as single crystals, but some-

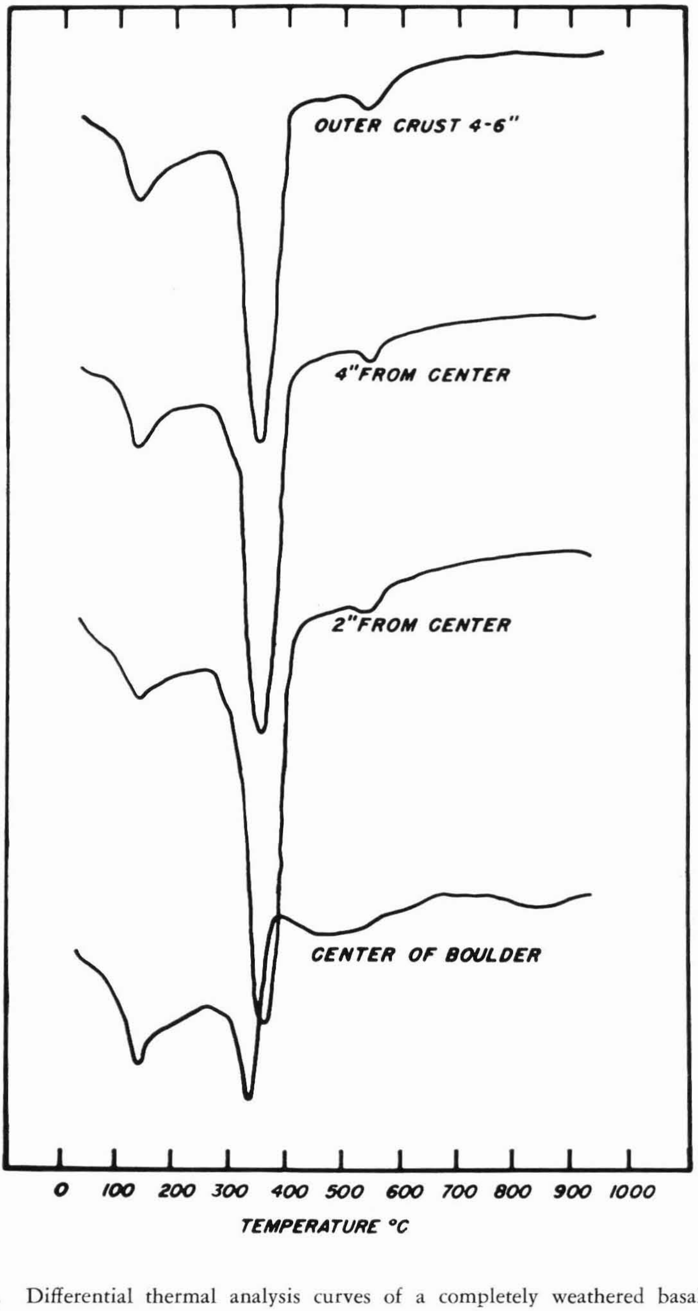


FIGURE 3. Differential thermal analysis curves of a completely weathered basalt boulder (saprolite).

times several crystals were adjoining or even interlocked and grown together; commonly, they had rounded boundaries; *augite* occurred in a wide range of sizes, but generally in intermediate sizes with numerous small crystals scattered throughout the matrix of the rock; *plagioclase* occurred as a mass of rather small laths in the interstices between the other components; *melilite* occurred in a similar manner to plagioclase, but less abundantly. The melilite had more relief than plagioclase; and opaque minerals *magnetite* and *chromite* occurred as small crystals sprinkled rather uniformly throughout the matrix.

Weathered portion of rock, 0 to 4 inches from core: This had a rather unorganized structure which in parts was totally unlike the rock and in other parts carried along a resemblance to the rock structure.

In the parts having the resemblance to the rock the feldspoid minerals were completely changed to gibbsite, usually in masses in the spaces occupied by the feldspar part of the matrix, but sometimes preserving vestiges of the lath shapes. The augite had been converted to a brown or yellowish-brown material which did not have much organized crystallinity, but which preserved the cleavage and other components of the augite structure. In some places this made an angular net of oriented crystallites resembling a honeycomb, with some cells empty, some filled with gel-like amorphous material, some with gibbsite. There were some large red goethite pseudomorphs after olivine. These were well crystallized and the crystallites were so well oriented that at first glance these pseudomorphs appeared to be single crystals, but close examination showed that they were aggregates. A few of these were hollow and occasionally one was filled with gibbsite.

Parts of this weathered portion of rock which did not preserve the rock structure as above comprised from one-fourth to one-third of the area of the sections. They seemed to be largely amorphous and consisted of alternating heavily and lightly iron-stained bands, rings, and patches, which were convoluted and intermixed, showing effects of rhythmic or intermittent precipitation in a gel (Liesegang rings). These amorphous-appearing parts did not seem to have any relation to the original rock. They may have started in pores, but they seemed larger than the pores. Pore origin is suggested by the fact that they often did not contain any of the magnetite crystals which were characteristically sprinkled in the crystallized gibbsitic portions about the same as in the rock.

4 to 5 inches from surface of rock core: This had a much more uniform and homogeneous structure than the 0- to 4-inch portion. Almost all of it maintained the structure of the rock with gibbsite having replaced the feldspar and possibly some of the augite; augite was replaced by brown, partly crystalline material which was oriented into networks; olivine was replaced by well-crystallized, oriented goethite. There was very little structure which would have gone through the amorphous or colloidal state described under the 0- to 4-inch portion. The only amorphous banded structure was at the edges of a few pores. Some late movement or enrichment in gibbsite was shown by coarse gibbsite crystal fillings in some pores.

5 to 6½ inches from surface of rock core: This was very much like the 4- to 5-inch portion, but had even better preservation of the structure of the rock. Gibbsite was dominant, replacing all the feldspar and some of the augite. Augite structure was well preserved by a lattice of brown iron oxide material. In the rock this lattice contained unfilled holes, but in this specimen all such spaces were filled with gibbsite. Olivine and possibly some of the larger augite phenocrysts were replaced by well-oriented, well-crystallized iron oxide. Some of these structures had hollow centers and some of the spaces were filled with gibbsite. The gibbsite crystals which filled such holes and filled the spaces in the augite skeletons were much coarser than the gibbsite that replaced the feldspar.

Outer crust, 6½ to 7½ inches from upper surface of rock core: Morphologically, this was very much like the 5- to 6½-inch portion, in a general way. However, there were some differences in detail and more variety in size, shape, and arrangement of components. The interstitial gibbsite matrix which occupied the place of the feldspar was much finer grained in most of the area in these sections than in the other three aforementioned. But much very coarse-grained gibbsite occurred in the seams and the cracks and as pore fillings.

It appeared that there had been some breakdown and rearrangement of components. Some patches were impregnated with yellowish-brown, high-iron material which looked as if it may have moved. Such patches appeared to be lower in gibbsite than the rest, suggesting that gibbsite had moved out locally, causing collapse. In several of these patches, pores were lined with definite thick coatings of oriented iron-stained kaolinitic clay (clay skins). This suggested that such patches are influenced by infiltration of clay from the soil above.

The results of the chemical and mineralogical examination of the rock and its weathering products have confirmed the belief that the ferruginous bauxite has developed under conditions which favored the rapid desilication of the primary silicates. This desilication has occurred under conditions which were not favorable to the formation of secondary alumino-silicate clays, as is evidenced by the total absence of these minerals at the point of weathering contact with the rock. This absence of silicate clay formation is probably due to insufficient silica concentration in the percolating water to support kaolinization or to a lack of sufficient duration of time of contact between silica and alumina molecules to permit their combining to form kaolin minerals. The free and rapid drainage of percolating waters would support either hypothesis. It is of interest to note that in every retarded drainage site found in this area the products of rock weathering had a high kaolin content.

Certain physical properties of the parent rock have played a role in the lack of resilication. The most important property is that these rocks are ultrabasic fine-grained porous boulders of a flow, probably *aa,* occurring on long moderate slopes which receive an annual rainfall of 100 to 200 inches. The surface soils have a high infiltration rate which decreases in the substratum, thus producing a condition favorable for the rapid lateral movement of water through the substratum. The porous nature of the rocks favors movement of water both into and out of the rock, thus producing effective free movement of leaching waters. The rocks become saturated due to their overall porosity. The fine texture of the rock and its saturated condition reduces aeration to a point where iron is both mobile and reactive, as a high portion is maintained in a ferrous condition at the rock margin during the process of desilication of the rock.

The presence and reactivity of the iron is demonstrated by the occurrence of the secondary mineral, nontronite, $Fe_2(SiAl)_4O_{10}(OH)_2$, at or near the contact zone between the rock and the weathered ferruginous bauxitic material (Sherman *et al.*, 1962). The nontronite occurs in pits on the surface of the rock core; in and around harder and slower weathering materials of the weathered rock; and, as pore fillings. The occurrence of this mineral in this weathering environment can only be ascribed to the reactive condition of iron, especially when there is no evidence of the formation of kaolin. The senior author was shown a similar occurrence of nontronite near Toowoomba, Queensland, Australia. The nontronite is transitory as it apparently decomposes to iron oxide, and the silica is lost.

The mobility of the iron is clearly demonstrated in the thin sections in which there are numerous instances of pore filling. This mobility also permits it to occur as iron oxide coatings on peds and as sheets.

Alumina occurs in two general forms. First, it is found as pseudomorphs after feldspars. Second, a large portion of the alumina is released in mobile form and moves to areas of concentration such as pore fillings, sheets, and coatings on peds. Its freedom from silication could readily be due either to concentration or to time.

This portion of the study has described the weathering processes which have developed the ferruginous bauxite, the parent material, on which the Halii soils have developed by pedogenic processes. As one studies the data presented to characterize the Halii soils, it will be noted that their parent material is very similar to the weathered portion of these rocks both in chemical composition and on mineralogical analysis.

CHEMICAL COMPOSITION OF HALII SOIL PROFILES

The samples from the three profiles of the Halii soils were analyzed for their chemical composition and the data obtained from these analyses are presented in tables 4, 5, and 6. The soil samples were separated into two fractions, nodules and soil, by screening with a sieve having 2-mm. openings. The samples were analyzed by standard fusion analysis methods described by Piper (1944) and by Jackson (1958). The following relationships were obtained from the chemical analysis of the three profiles:

1. *Nodules:* The percentage of the nodules was the highest in the soil horizons near the surface. The content of nodules decreased with depth ranging from 76 to 3 percent in the profile from the northwest slope; 68 to 3 percent in the profile from the northern slope; and, 85 to 8 percent in the profile from the southwest slope of Kilohana Crater.

The chemical composition of the nodules was, in general, quite uniform. The chief difference was found in the high iron oxide content in the polished shiny-surfaced nodules of the profiles from the northern and southwest slopes of Kilohana

TABLE 4.

Chemical composition of Halii Gravelly Clay from a deep pit dug by bauxite mining company on northwest slope of Kilohana Crater, Kauai

SAMPLE NO. AND DEPTH	SAMPLE FRACTION	PERCENTAGE OF WHOLE	SiO_2, PERCENT	Al_2O_3, PERCENT	TOTAL Fe_2O_3, PERCENT	FeO, PERCENT	TiO_2, PERCENT	MnO, PERCENT	CaO, PERCENT	MgO, PERCENT	K_2O, PERCENT	Na_2O, PERCENT	pH	L.O.I.
2-2-1	nodule	23.9	1.1	57.0	14.0	0.5	1.6	0.07	0.02	0.10	0.01	0.26		28.5
0–5 inches	soil	76.1	1.5	26.4	46.9	1.5	6.0	0.10	0.05	0.60	0.10	0.12	5.1	19.3
2-2-2	nodule	24.5	1.4	49.1	23.2	1.5	2.8	0.08	0.05	0.23	0.03	0.24		25.3
5–18 inches	soil	75.5	2.4	25.5	48.7	2.3	6.2	0.09	0.04	0.33	0.11	0.50	4.9	18.7
2-2-3	nodule	indurate	0.8	57.0	14.5	0.0	1.6	0.06	0.04	0.11	0.01	0.30		28.2
18–20 inches	soil	material	1.5	38.5	35.5	0.3	4.4	0.09	0.03	0.28	0.08	0.38		21.6
2-2-4	nodule	10.6	1.2	54.5	16.5	0.6	1.9	0.06	0.04	0.33	0.02	0.29		27.7
20–30 inches	soil	89.4	2.3	26.1	48.3	1.6	6.2	0.13	0.05	0.64	0.11	0.42	5.1	17.5
2-2-5	indurate	indurate	1.1	55.4	17.4	0.9	1.8	0.08	0.04	0.29	0.008	0.37		26.9
40–43 inches	layer	material												
2-2-6	rock	indurate	1.3	52.6	18.2	1.8	2.0	0.09	0.03	0.32	0.004	0.24		26.5
72–74 inches	clay	material	3.2	36.8	35.6	2.1	4.2	0.15	0.05	0.63	0.06	0.50		19.6
2-2-7	nodule	7.2	2.2	49.1	21.9	1.6	2.6	0.10	0.03	0.38	0.03	0.61		24.5
80–85 inches	soil	92.8	4.5	26.1	48.5	2.8	6.4	0.14	0.04	0.67	0.09	0.71	5.2	15.9
2-2-8	nodule	6.1	3.1	52.6	19.5	1.3	2.1	0.09	0.03	0.22	0.008	0.48		25.2
125–130 inches	soil	93.9	6.3	35.6	36.4	2.8	4.5	0.17	0.03	0.55	0.03	0.17	5.4	18.4
2-2-9	nodule	3.0	4.1	54.2	16.4	0.5	1.8	0.10	0.03	0.40	0.02	0.31		25.7
158–163 inches	soil	97.0	10.2	31.8	38.1	1.2	4.6	0.19	0.04	0.88	0.03	0.53	5.2	16.2

TABLE 5. Chemical composition of Halii Gravelly Clay from a pit dug on northern slope of Kilohana Crater, Kauai

SAMPLE NO. AND DEPTH	SAMPLE FRACTION	PER-CENTAGE OF WHOLE	SiO_2, PERCENT	Al_2O_3, PERCENT	TOTAL Fe_2O_3, PERCENT	FeO, PERCENT	TiO_2, PERCENT	MnO, PERCENT	CaO, PERCENT	MgO, PERCENT	K_2O, PERCENT	Na_2O, PERCENT	pH	L.O.I.
2-3-1	nodule	68.5	1.0	14.2	62.7	1.9	3.7	0.06	0.04	0.02	0.04	0.71		19.5
0–3 inches	soil	30.7	4.2	17.6	51.1	4.1	4.5	0.07	0.05	0.08	0.07	0.56	4.5	23.9
2-3-2	nodule	65.8	2.1	17.0	57.3	1.5	3.4	0.08	0.04	0.05	0.05	0.79		20.2
3–6 inches	soil	34.1	6.4	20.2	46.8	3.2	4.9	0.08	0.06	0.08	0.09	0.48	4.5	23.2
2-3-3	nodule	55.9	1.7	29.0	44.1	1.0	3.4	0.07	0.03	0.06	0.08	0.55		22.6
6–15 inches	soil	44.1	3.9	27.0	41.1	2.1	5.7	0.05	0.03	0.07	0.17	0.50	4.7	24.8
2-3-4	nodule	23.3	0.9	49.0	23.4	0.9	2.4	0.08	0.03	0.08	0.02	0.64		25.8
15–18 inches	soil	76.7	1.3	28.7	43.8	1.1	5.4	0.08	0.03	0.17	0.09	0.56		20.8
2-3-5	nodule	13.7	0.8	57.0	15.5	0.2	1.7	0.06	0.02	0.06	0.03	0.71		28.1
18–24 inches	soil	86.3	1.2	27.6	46.8	1.1	4.4	0.11	0.04	0.22	0.09	0.81	5.1	18.7
2-3-6	nodule	7.6	1.0	55.3	13.8	0.1	1.6	0.05	0.02	0.07	0.02	0.61		29.0
24–26 inches	soil	92.4	1.7	29.8	43.5	0.6	5.7	0.09	0.03	0.09	0.11	0.87	4.9	21.1
2-3-7	nodule	15.1	0.7	55.9	13.9	0.3	1.6	0.05	0.04	0.04	0.02	0.74		28.8
26–31 inches	soil	84.9	1.8	25.3	48.7	1.1	6.5	0.11	0.06	0.42	0.08	0.94	4.9	18.2
2-3-8	nodule	9.3	1.0	55.6	15.3	0.2	1.6	0.06	0.04	0.07	0.02	0.46		27.8
31–52 inches	soil	90.7	1.8	29.7	44.8	0.7	6.0	0.10	0.04	0.21	0.09	1.05	5.1	19.4
2-3-9	nodule	15.8	1.0	54.2	16.3	0.6	1.9	0.06	0.04	0.09	0.01	0.36		27.7
52–80 inches	soil	84.2	2.2	33.2	39.6	0.9	5.1	0.11	0.06	0.25	0.06	0.82	5.3	19.4
2-3-10	nodule	3.3	1.1	52.9	17.1	0.1	1.9	0.07	0.04	0.10	0.01	0.63		27.3
80–85 inches	soil	96.7	2.8	32.6	41.7	0.6	5.5	0.12	0.06	0.26	0.06	0.80	5.1	18.6

TABLE 6. Chemical composition of Halii Gravelly Clay from a pit dug on southwest slope of Kilohana Crater, Kauai

SAMPLE NO. AND DEPTH	SAMPLE FRACTION	PERCENTAGE OF WHOLE	SiO_2, PERCENT	Al_2O_3, PERCENT	TOTAL Fe_2O_3, PERCENT	FeO, PERCENT	TiO_2, PERCENT	MnO, PERCENT	CaO, PERCENT	MgO, PERCENT	K_2O, PERCENT	Na_2O, PERCENT	pH	L.O.I.
2-4-1	nodule	60.4	7.5	17.1	39.8	5.9	5.0	0.05	0.13	0.22	0.09	0.18		31.2
0–3 inches	soil	39.3	7.1	17.1	40.8	6.4	4.9	0.05	0.15	0.20	0.09	0.32	4.8	30.9
2-4-2	nodule	85.1	0.5	9.2	69.7	0.8	3.1	0.03	0.12	0.06	0.03	0.47		18.6
3–8 inches	soil	14.9	3.0	11.8	61.8	2.1	4.2	0.04	0.10	0.06	0.04	0.34	4.1	20.3
2-4-3	nodule	73.7	1.1	13.9	63.4	0.8	3.5	0.03	0.05	0.06	0.04	0.41		19.0
8–10 inches	soil	26.3	5.2	12.5	60.4	1.1	5.1	0.03	0.04	0.08	0.06	0.27	4.3	18.4
2-4-4	rock	—	1.0	45.0	27.3	1.7	2.7	0.03	0.04	0.11	0.02	0.88		25.5
10–19 inches	clay	—	2.0	29.5	43.1	1.8	6.2	0.06	0.06	0.12	0.08	0.66		20.9
2-4-5	nodule	33.8	0.6	49.1	22.9	1.3	2.8	0.03	0.03	0.11	0.01	0.55		25.7
19–31 inches	soil	66.2	0.8	27.1	47.6	1.8	6.5	0.07	0.05	0.16	0.06	0.46	5.1	18.8
2-4-6	nodule	18.0	0.8	59.4	10.4	0.0	1.2	0.02	0.03	0.08	0.02	0.87		30.1
31–33 inches	soil	82.0	1.0	35.1	38.4	0.2	4.9	0.04	0.05	0.17	0.06	0.80	5.2	21.7
2-4-7	nodule	15.8	0.7	56.6	14.5	0.1	1.7	0.04	0.04	0.17	0.02	0.81		28.6
33–42 inches	soil	84.2	1.0	30.7	43.9	0.5	5.8	0.09	0.07	0.51	0.06	1.12	5.2	19.2
2-4-8	rock	—	0.5	45.0	29.2	1.1	3.3	0.06	0.06	0.09	0.01	0.93		24.3
42–54 inches	clay	—	0.8	32.6	42.1	1.8	5.6	0.06	0.08	0.17	0.03	0.93		19.4
2-4-9	nodule	8.4	0.8	52.8	17.8	0.4	2.1	0.03	0.06	0.24	0.01	0.38		27.1
54–66 inches	soil	91.6	0.9	27.0	48.9	1.5	6.4	0.10	0.06	0.87	0.05	1.01	5.3	16.8

Crater. The iron oxide content of these nodules ranged from 57 to 70 percent, while the alumina content ranged from 14 to 20 percent. Only the nodules from the 0- to 3-inch horizon of the profile from the southwest slope had an appreciable silica content, 7.5 percent. Likewise, this sample was the only sample to have an appreciable content of ferrous iron. The only other variation in analysis was the higher calcium content of the nodules of the surface samples of the profile from the southwest slope.

The range and the average analysis of major constituents of the other nodules are as follows: SiO_2 content ranged from 0.5 to 4.1 percent with an average of 1.23 percent; Al_2O_3 content ranged from 45.0 to 59.4 percent with an average of 52.23 percent; and Fe_2O_3 content ranged from 10.4 to 29.2 percent with an average of 18.03 percent. The ferrous oxide content was low, amounting to about 4-plus percent of the total iron oxide content. The content of titanium oxide was low, ranging from 1.2 to 5.0 percent. The content of MnO, CaO, MgO, K_2O, and Na_2O amounted to less than 1 percent in all nodules with sodium being the highest oxide. Calcium was extremely low in all nodules. The loss on ignition was high for all nodules, ranging from 18 to 31 percent.

2. *Soil:* The soil content of the samples increased with depth. However, it should be noted that if the soil were to dry, the content of nodules in the soil would increase because of the aggregation resulting from the dehydration of hydrous gels of iron and aluminum oxides. The soil may be divided into three kinds of materials, namely: soil of the ferruginous nodule surface horizons; soil of two indurated layers in the profile on the northwest slope; and, predominant soil of the other soil horizons.

The average chemical composition of the soils from the ferruginous surface is as follows: SiO_2 content, 4.1 percent; Al_2O_3 content, 17.3 percent; and Fe_2O_3 content, 57.8 percent. The average analysis of the soil material from the indurated layers is as follows: SiO_2 content, 2.3 percent; Al_2O_3 content, 37.7 percent; and Fe_2O_3 content, 35.5 percent. The range and the average analysis of the majority of the soil samples are as follows: SiO_2 content ranged from 0.8 to 10.2 percent with an average of 2.90 percent; Al_2O_3 content ranged from 17.1 to 35.6 percent with an average of 28.4 percent; and Fe_2O_3 content ranged from 36.4 to 48.9 percent with an average of 44.03 percent. The ferrous iron content was higher in the soil than it was in the nodules but the proportion of ferrous to ferric iron was lower in the soil. The titanium oxide content was markedly higher in the soil, ranging from 4.2 to 6.5 percent. The calcium oxide content was extremely low. The content of MnO, CaO, MgO, K_2O, and Na_2O was very low, amounting to about 1 percent. These oxides were all higher in the soil than in the nodules. The loss on ignition ranged from 15.9 to 24.8 percent, excluding the surface sample from the profile of the southwest slope of Kilohana Crater.

The chemical composition of the soil profile has its greatest variation in the surface horizon. The profiles from the northern and southwest slopes have a surface horizon of ferruginous nodules. The depth of the ferruginous horizon varies throughout the area from a thin layer of an inch or so to more than a foot in thickness. The ferruginous layer is absent in the profile on the northwest slope of Kilohana Crater. This may be due to erosion as it lacks the evidence of alumino-silicate clay in the surface horizon. Otherwise, the chemical composition of the profiles is very uniform. The data demonstrate the pedogenetic processes of soil development on a completely weathered ferruginous bauxite retaining its original rock structure and devoid of silica, silicates, and bases. The saprolite with rock structure is lacking only in the surface and near-surface horizons.

BULK DENSITY MEASUREMENTS

Samples were collected for bulk density measurements from the Halii soil profile pit located on the southwest slope of Kilohana Crater. A definite volume of soil was taken from the field and dried at 105° C. The bulk density was calculated after weighing the dried sample. The data obtained are presented in table 7. The surface horizon has a bulk density of 1.60. The other selected samples of the profile were rather uniform in their bulk density, as the range was from 1.05 to 1.21 with averages of approximately 1.14.

TABLE 7. Percent moisture and bulk density of Halii Gravelly Clay from pit dug on southwest slope of Kilohana Crater, Kauai

DEPTH, INCHES	MOISTURE, PERCENT	BULK DENSITY	DEPTH, INCHES	MOISTURE, PERCENT	BULK DENSITY
8–10	24.0	1.60	33–42	57.6	1.09
10–19	54.8	1.10	42–54	43.2	1.12
10–19	50.1	1.13	54–66	47.9	1.16
10–19	42.6	1.15	54–66	48.0	1.15
33–42	49.6	1.21	54–66	46.1	1.17
33–42	59.8	1.05			

EXCHANGE CAPACITY AND EXCHANGEABLE CATIONS

The exchange capacity and the exchangeable cations were determined on the soil fraction of the samples of the horizons of all three profiles from the slopes of Kilohana Crater. The cation exchange capacity was determined by using normal sodium acetate as the exchanging cation. The sodium was then displaced by a 4 percent KCl solution and determined in the filtrate by the Beckman flamephotometer. The exchangeable cations were replaced by a normal neutral ammonium acetate and determined by methods described by Piper (1944) and Jackson (1958). Exchangeable hydrogen was determined in the ammonium acetate leachate by potentiometric titration. The data obtained by these analyses are presented in tables 8, 9, and 10.

The data presented in table 8 are those obtained from the analysis of the highly bauxitic profile from the northwest slope of Kilohana Crater. This profile had the lowest cation exchange capacity of the three profiles ranging from 3.8 to 13.7 milliequivalents per 100 grams. The exchangeable bases were extremely low. The sum of the exchangeable cations did not equal the exchange capacity which is characteristic of amorphous hydrated iron and aluminous oxides.

The data obtained from the analysis of the Halii profile from the northern slope of Kilohana Crater are presented in table 9. The cation exchange capacity and the exchangeable aluminum content were the highest in the ferruginous surface horizons 0- to 3-, 3- to 6-, and 6- to 15-inch depths. The bauxitic horizons below the 15-inch depth were similar in exchange capacity and exchangeable cations to the bauxitic horizons found in the profile from the northwest slope, except that the exchangeable calcium was slightly higher.

TABLE 8. Cation exchange capacity and exchangeable cation content of the soil fractions of the Halii Gravelly Clay from a pit dug by an aluminum company on the northwest slope of Kilohana Crater, Kauai

DEPTH, INCHES	CATION EXCHANGE CAPACITY	MILLIEQUIVALENTS PER 100 GRAMS							
		H	Ca	Mg	K	Na	Mn	Fe^{++}	Al
0–5	12.26	2.53	0.17	0.05	T*	0.18	T	0.03	0.03
5–18	13.67	4.23	0.21	0.05	T	0.11	T	0.08	0.03
20–30	10.12	1.26	0.17	0.04	0.03	0.08	T	0.11	0.03
80–85	5.14	2.52	0.25	0.05	0.11	0.13	T	1.35	0.03
125–130	3.83	1.66	0.37	0.04	0.03	0.09	0.01	0.15	0.03
158–163	5.57	3.35	0.39	0.02	0.04	0.14	T	0.29	0.05

* Trace.

TABLE 9. Cation exchange capacity and exchangeable cations in a profile of the Halii Gravelly Clay from the northern slope of Kilohana Crater, Kauai

DEPTH, INCHES	CATION EXCHANGE CAPACITY	MILLIEQUIVALENTS PER 100 GRAMS							
		H	Ca	Mg	K	Na	Mn	Fe^{++}	Al
0–3	25.84	23.03	0.51	0.05	0.10	0.15	0.01	0.21	0.62
3–6	25.88	21.45	0.41	0.07	0.06	0.14	T*	0.11	0.73
6–15	23.37	18.95	0.31	0.06	0.10	0.14	T	0.24	0.38
15–18	10.06	5.01	0.27	0.05	0.10	0.14	0.01	0.20	0.05
18–24	10.17	3.35	0.33	0.06	0.04	0.11	0.01	0.23	0.03
24–26	12.31	4.63	0.81	0.05	0.04	0.14	T	0.03	0.03
26–31	9.98	3.75	0.39	0.04	0.03	0.14	T	0.03	0.03
31–52	8.51	3.33	0.33	0.05	0.03	0.14	T	0.02	0.03
52–80	6.29	1.66	0.40	0.04	0.06	0.15	T	0.14	0.03
80–85	6.69	2.52	0.37	0.05	0.06	0.15	T	0.06	0.03

* Trace.

TABLE 10. Cation exchange capacity and exchangeable cations of a profile of the Halii Gravelly Clay from the southwest slope of Kilohana Crater, Kauai

DEPTH, INCHES	CATION EXCHANGE CAPACITY	MILLIEQUIVALENTS PER 100 GRAMS							
		H	Ca	Mg	K	Na	Mn	Fe^{++}	Al
0–3	44.42	22.61	18.05	2.24	0.52	0.33	0.04	0.02	0.48
3–8	22.70	12.38	8.41	0.35	0.09	0.09	T*	0.05	0.08
8–10	20.40	11.90	2.84	0.08	0.05	0.08	T	0.03	0.11
19–31	10.25	6.25	3.81	0.03	0.03	0.04	T	0.03	0.03
31–33	8.13	5.94	1.32	0.03	0.03	0.03	T	0.03	0.03
33–42	6.75	5.75	1.91	0.09	0.04	0.06	T	0.02	0.03
54–66	9.68	6.51	3.37	0.20	0.04	0.04	T	0.03	0.03

* Trace.

The data presented in table 10 show the cation exchange capacity and exchangeable cation content of the Halii profile from the southwest slope of Kilohana Crater. The ferruginous surface horizons had a high cation exchange capacity, ranging from 20 to 44 milliequivalents per 100 grams. The bauxitic subsoil was similar to the bauxitic subsoils of the other slopes of Kilohana Crater. The high exchangeable base level of the surface soil was due to the application of lime to this area. This fact was ascertained after the analysis. The lime was stockpiled near the location of this profile. The exchangeable calcium was very high at the surface but decreased with depth; however, it was still much higher than the other profiles. The exchangeable magnesium and potassium were only markedly higher in the very surface horizon, 0 to 3 inches.

MINERAL IDENTIFICATION BY DIFFERENTIAL THERMAL ANALYSIS

Mineral identification of the samples from the three Halii Gravelly Clays was made by differential thermal analysis methods proposed by Norton (1939). The differential thermal curves obtained are presented in figures *4a, 4b, 5a, 5b, 6a,* and *6b*. Figures *4a, 5a,* and *6a* present the curves for the three soils, and figures *4b, 5b,* and *6b* present the curves for the corresponding nodule samples.

The curves presented in figure *4b* were obtained by the thermal analysis of the samples from the profile of the Halii Gravelly Clay from the northwest slope of Kilohana Crater. The curves are those from a fragment. All of these curves have a strong endothermic action at 340° C. and weaker endothermic action at 540° C. The strong endothermic action is that of gibbsite and the weaker is due to traces of kaolin or possibly boehmite. The curves in figure *4a* indicate a much lower content of gibbsite as shown by lower endothermic action at 320° C. to 340° C. The strong exothermic action at 400° C. plus is due to the crystallization of amorphous iron oxides, possibly to maghemite. This is in keeping with the increase in magnetism of these samples on drying and their low ferrous iron content. Thus, these soils are largely aggregates of gibbsite containing small amounts of maghemite and a soil containing about equal amounts of gibbsite and a mixture of amorphous iron oxides. The goethite-hematite system is also present. According to Matsusaka and Sherman (1961) the evidence for the existence of crystalline lepidocrocite is weak.

The differential thermal curves presented in figures *5a, 5b, 6a,* and *6b* show the same relationships for the bauxitic subsoils for the Halii profiles from the northern and southwest slopes of Kilohana Crater. The ferruginous surface layers show very different thermal properties. The nodules have endothermic peaks at 145° C. and 310° C. The endothermic peak at 310° C. is followed by a broad exothermic reaction. These thermal analyses suggest a mixture of goethite and amorphous material. The soils of the ferruginous horizons have similar thermal characteristics and, thus, a similar mineral composition. The endothermic action at 145° C. is probably due to small amounts of allophane or amorphous free oxides, plus organic matter.

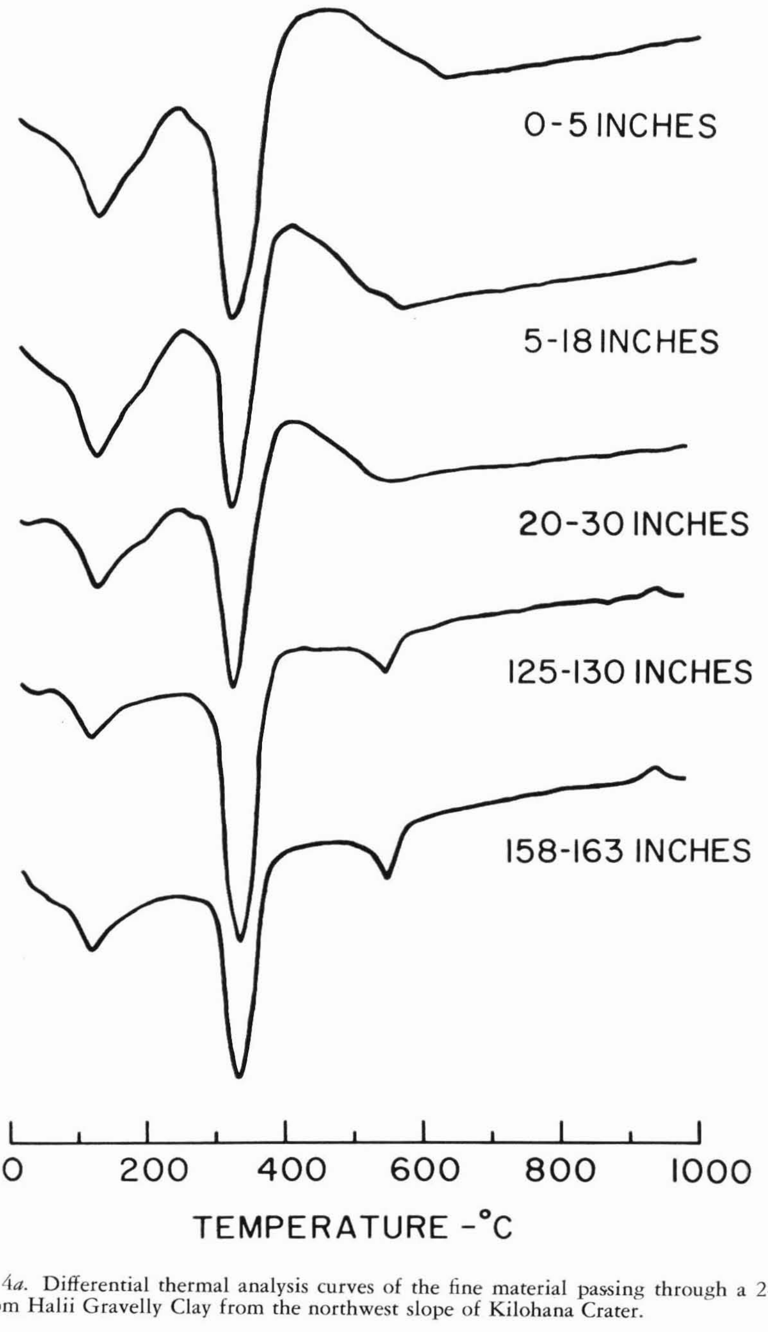


FIGURE 4*a*. Differential thermal analysis curves of the fine material passing through a 2-mm. sieve from Halii Gravelly Clay from the northwest slope of Kilohana Crater.

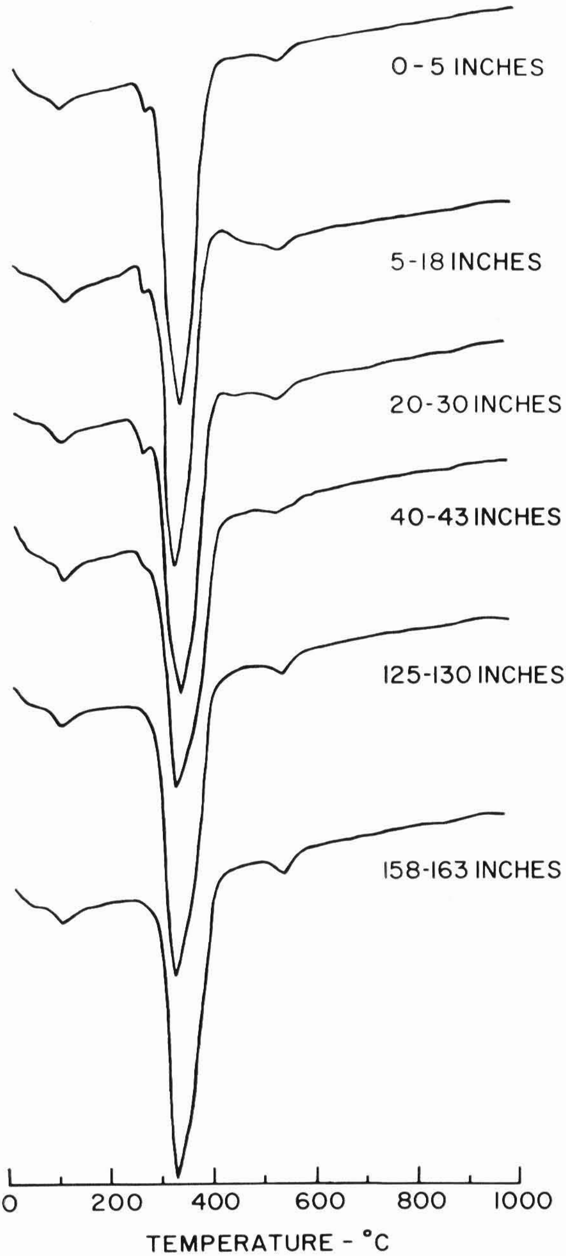


FIGURE 4*b*. Differential thermal analysis curves of the nodules from Halii Gravelly Clay from the northwest slope of Kilohana Crater.

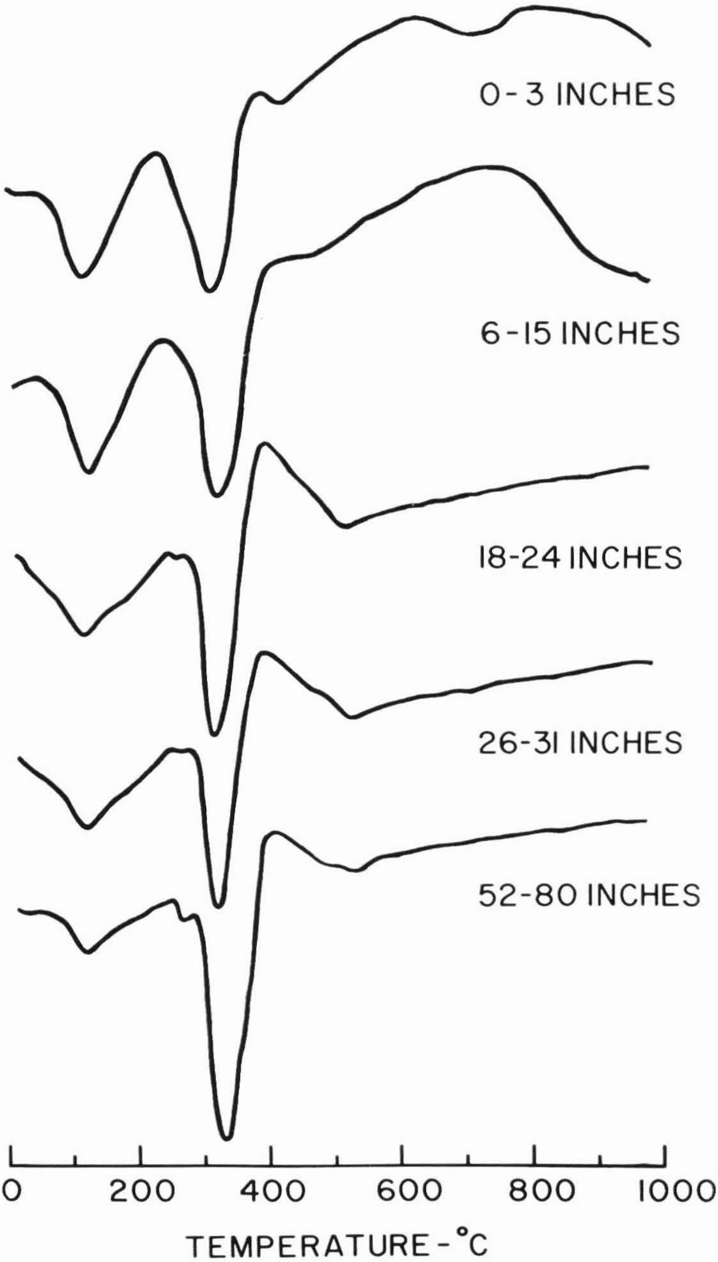


FIGURE 5*a*. Differential thermal analysis curves of the fine material passing through a 2-mm. sieve from Halii Gravelly Clay from the northern slope of Kilohana Crater.

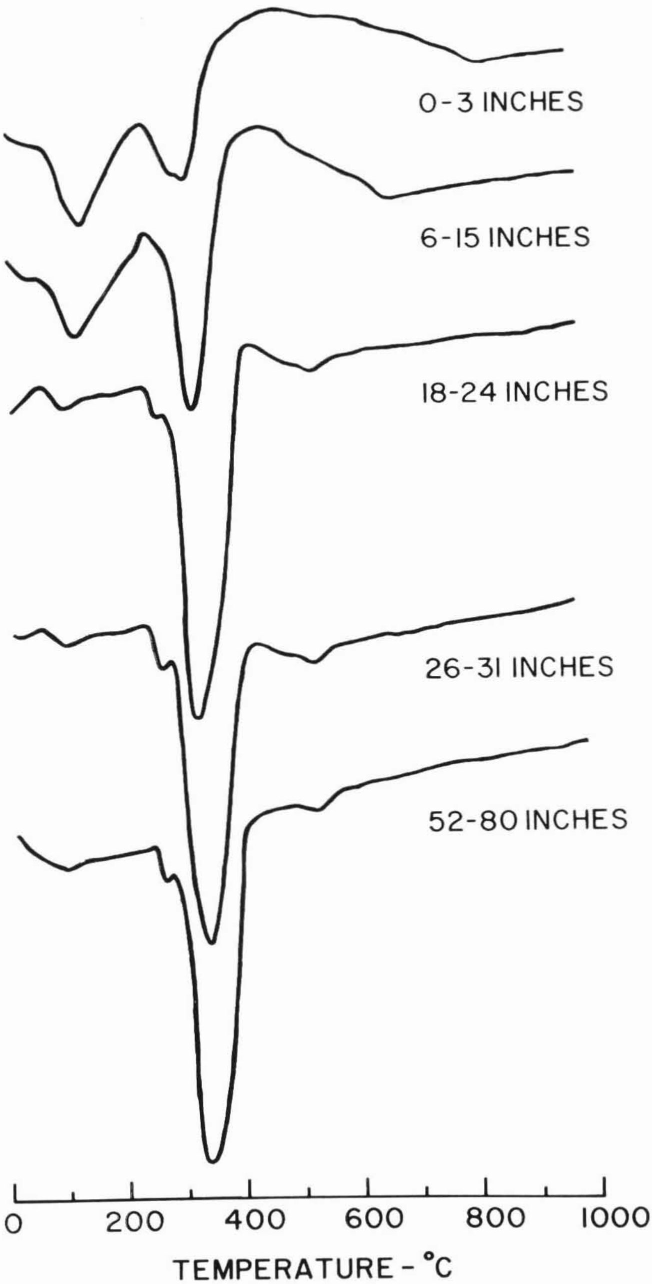


FIGURE 5*b*. Differential thermal analysis curves of the nodules from Halii Gravelly Clay from the northern slope of Kilohana Crater.

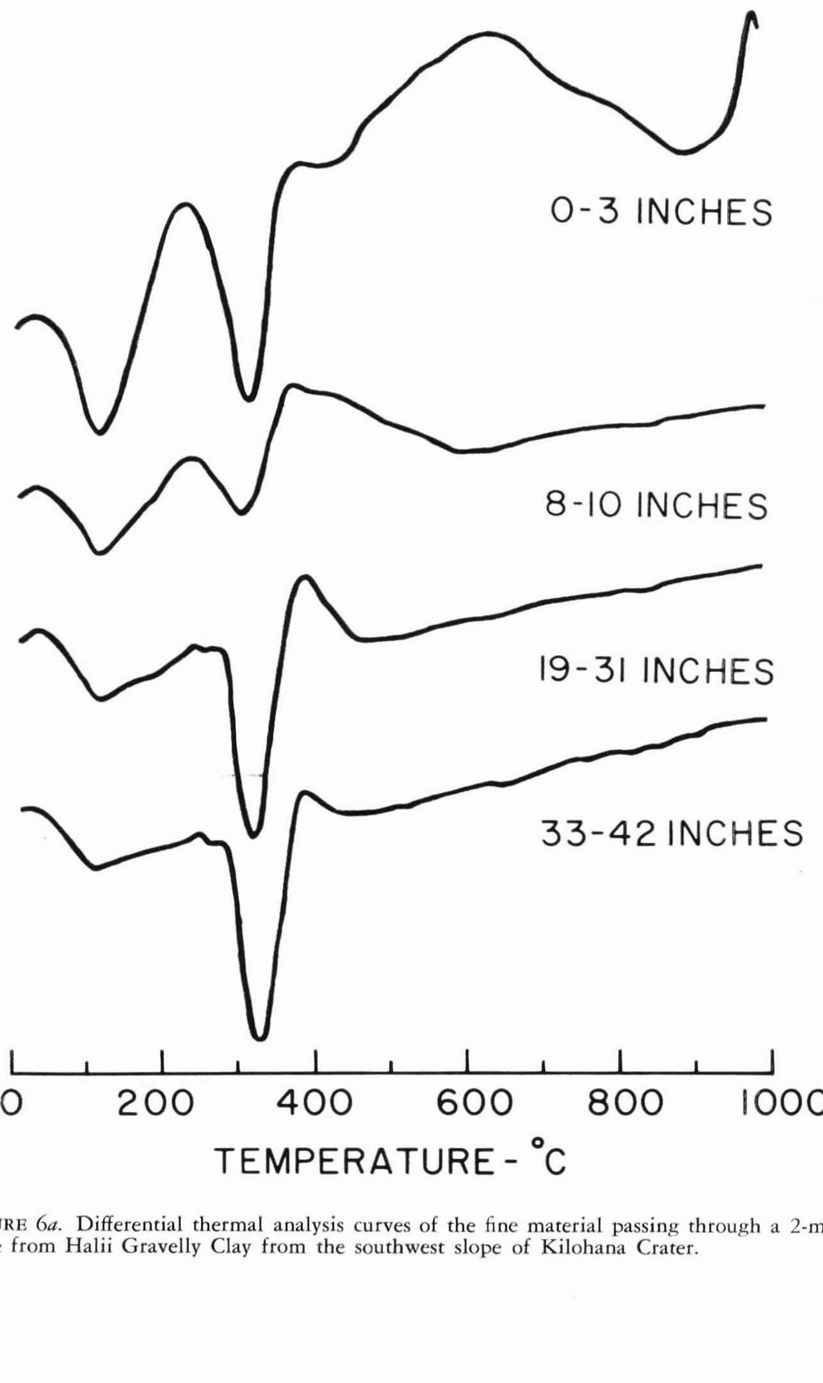


FIGURE 6*a*. Differential thermal analysis curves of the fine material passing through a 2-mm. sieve from Halii Gravelly Clay from the southwest slope of Kilohana Crater.

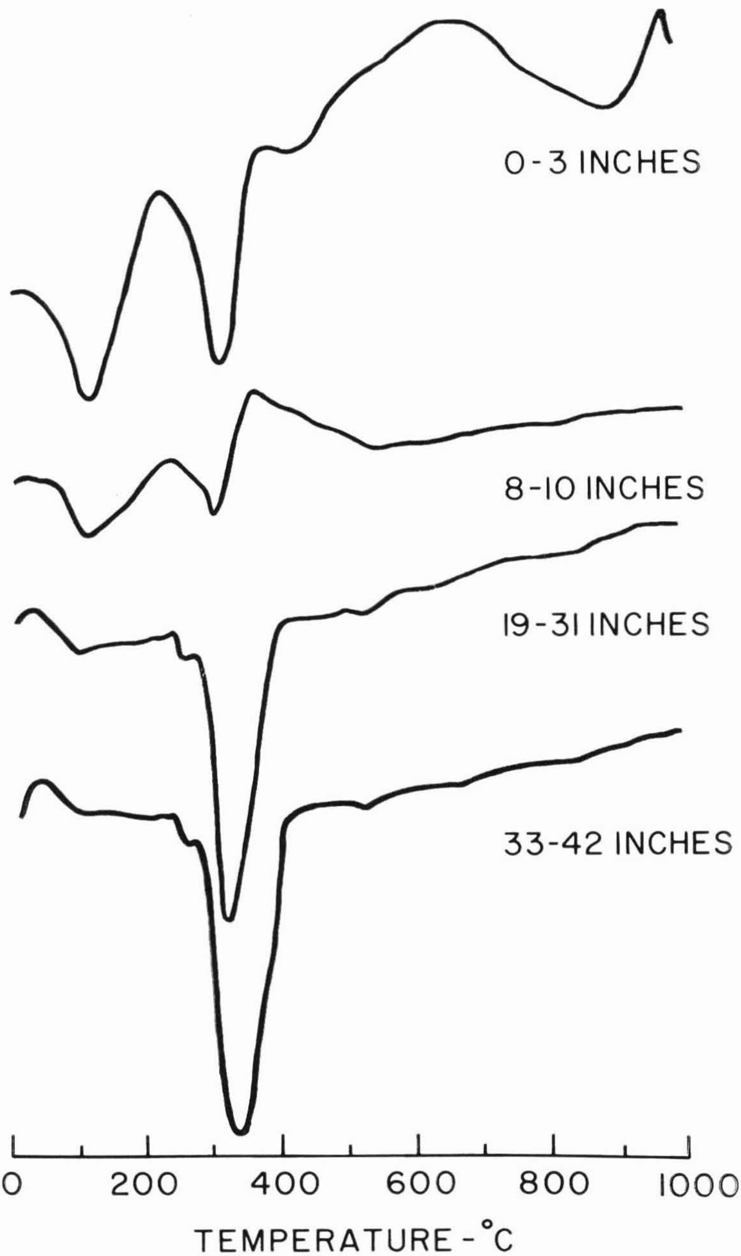


FIGURE 6*b*. Differential thermal analysis curves of the nodules from Halii Gravelly Clay from the southwest slope of Kilohana Crater.

IDENTIFICATION OF MINERALS AND WEATHERING PROCESSES BY OPTICAL METHODS USING THIN-SECTION TECHNIQUE

The samples from the three profiles from the slopes of Kilohana Crater were examined by thin-section technique. The microscopic examinations of the thin sections resulted in the following detailed observations.

Halii Gravelly Clay Profile from Pit on Northwest Slope of Kilohana Crater

0 to 5 inches: Groundmass brownish in transmitted light. Not much arrangement of material: some areas have a sort of coarse, ball structure and there are variations in density—parts are clear and light colored, others cloudy and darker; the whole is sprinkled with gibbsite crystals of various sizes; some large aggregates of pure fine-grained gibbsite; numerous red, well-crystallized pseudomorphs of goethite after olivine and possibly also after augite. There are some fragments of various sizes which retain the basalt structure with gibbsite after the feldspar laths, large goethite-after-olivine pseudomorphs, and crystals of magnetite or chromite. These are quite distinct and different from the matrix, but do not have sharp boundaries separating them from it. They seem to have a merging or transitional boundary. This does not eliminate the possibility that some addition of other material occurred. Perhaps a large part of the matrix has passed through soil fauna.

5 to 18 inches: This is somewhat different from the surface layer—quite different in structure but obviously about the same composition. The matrix consists of translucent reddish-brown material with little structure except for a tendency to occur in rough balls and irregular blocks. It is sprinkled with gibbsite crystals of various sizes, goethite pseudomorphs after olivine, and opaque bodies. Both the gibbsite crystals and the pseudomorphs are larger than in the rock samples. There is a larger proportion of the material with basalt structure and this is more definitely transitional to the matrix around the edges than in the rock.

This is closely related to rock, but is more disturbed and weathered.

18 to 20 inches: This sample is quite different from the preceding samples. The physical structure of rock of Hawaiian lava flows differs greatly over short distances. The structure is coarser and there are relatively few of the olivine pseudomorphs, but the ones present are very large.

General appearance is a coarsely vesicular material with most of the spaces filled with rather fine granular gibbsite randomly arranged. The bridging material between retains some basalt structure with feldspar laths substituted by gibbsite, some olivine pseudomorphs, and opaques. Through this are involuted bands of reddish microcrystalline material which shows birefringence, but with the crystals oriented perpendicular to the bands rather than parallel as in clay skins; this material is probably goethite formed in place from solution.

20 to 30 inches: The matrix of most of sections is fairly smooth, translucent reddish-brown, sprinkled with opaques, and with little structure. Much of this consists of very fine gibbsite (1 micron or less). Imbedded in this with great variation in density are the common olivine pseudomorphs; in places these are stacked very closely, in other places they are absent. Where the phenocrysts are dense, the opaques are much more abundant, indicating collapse or removal of interstitial material. Gibbsite of visible size is mostly concentrated in large aggregates in what appear to be pore fillings. No lath and phenocrysts basalt structure was seen.

40 to 43 inches: All the sections show perfectly preserved weathered basalt structure with the red, well-organized pseudomorphs after olivine, feldspar laths substituted by gibbsite, and brown clayey-appearing material occupying the place of the augite. There has been no collapse or volume change. Many of the vesicles are empty, with just a rim of gibbsite around them; others are almost full; others in between. No evidence of movement of anything excepting aluminum is indicated by this cavity filling. Most of the opaques are delicate little branched crystallites.

72 to 74 inches: This is different from preceding sample, though it resembles it in composition. Red, well-crystallized olivine pseudomorphs, gibbsite, opaques, and brownish interstitial material are the components. Evidence of the basalt structure is not pronounced, though there is enough to suggest that there has not been much collapse or volume change. It appears that the original basalt was different. Phenocrysts are larger and more abundant. Opaques are more abundant and are small cubes instead of dendrites. Laths where visible are large and interstitial material is less evident. Pores are more numerous, but tend to be smaller. There is less evidence for filling of pores with gibbsite; instead, most pores seem to be lined with a thin coat of dense brown material. Many of the lath shapes are empty.

80 to 85 inches: This is very much like the 20- to 30-inch layer. Smooth translucent reddish matrix with phenocrysts and opaques and irregular distribution of these and the gibbsite. One different feature was noted. Large cracks filled with pale translucent reddish-yellow material free from opaques showing aggregate extinction which could be a clay skin. The variation in concentration of phenocrysts, opaques, and gibbsite is more pronounced than in the 20- to 30-inch layer. These tend to be concentrated in pockets. The fact that the smooth matrix contains all three, more widely spaced, suggests some local collapse and removal of material.

125 to 130 inches: This has the weathered basalt composition and structure again. Composition is the same as others described thus, but structure is slightly different. Structure is moderately coarse, porosity low. The brown, clayey interstitial material is fairly abundant. Pores are beginning to fill with gibbsite.

158 to 163 inches: Very similar to 125- to 130-inch layer except that the brown, clayey interstitial material is more abundant and gibbsite occurs in coarser crystals. Porosity or vesicularity is low and if pores occur, they are large. Pores lined with clear gibbsite, but deposition may have stopped for there is a thin, brown coating on the surface of the gibbsite. A small amount of downward movement of amorphous iron oxide and traces of clay is indicated by the occurrence of the brown material described.

Halii Gravelly Clay Profile from Pit on Northern Slope of Kilohana Crater

0 to 3 inches: The sections were made from the hard fragments. These have the weathered basalt structure and composition as described in several horizons of profile from northwest slope. There are some areas of the smooth translucent material with involution and ball structure which appear to be fills in large pores or channels.

3 to 6 inches: No large coherent pieces were available. Sections were made of loose material impregnated together. Some of this is earthy, dark-brown material with a sprinkling of gibbsite crystals and fragments of phenocrysts. Some large grains are fragments of weathered basalt. There are also some round concretions with rather heavy iron impregnation, unorganized earthy material with interspersed phenocryst pseudomorphs, and a rather dense and hard skin.

6 to 15 inches: The sections of this horizon show mostly translucent brownish material with little structural organization. Grains of gibbsite and red goethite fragments are rather uniformly scattered throughout. There are some large nodules of pure gibbsite aggregates and some bodies which are most densely impregnated with iron and which contain phenocryst pseudomorphs. Also fragments of weathered basalt with structure preserved. The material is rather porous with an assortment of cracks, crevices, and pores, but no coatings or fillings were seen on the surfaces of these.

15 to 18 inches: Structure here appears more complex than in most of the other horizons. Composition: gibbsite; iron oxide in olivine pseudomorphs and other forms; amorphous-appearing brownish and reddish material; opaque material. Overall, the specimens retain some structural appearance of weathered vesicular basalt, as shown by the pseudomorphs, lath forms filled with gibbsite, and arrangement of opaques. Much of the opaque is dendritic crystallites. There seems to have been much rearrangement of material by solution and reprecipitation, or gel formation and movement shown by involuted bands of amorphous brown material and gibbsite. Gibbsite fills the vesicles and pores and is present in thin bands wandering along surfaces of most openings. These gibbsite coatings are the most striking feature. In many of the channels and pores a brown claylike material is banded sometimes along with the gibbsite, sometimes alone. It does not show any birefringence, however.

18 to 24 inches: Except for the presence of olivine pseudomorphs and abundant gibbsite this has little resemblance to the preceding horizon. Only in a few small patches is basalt structure retained and in these patches it does resemble parts of it. There are balls and channels, filled with granular gibbsite, which look as if they once had been basalt vesicles. Between these is a variety of material and structures. Most of it is brown translucent earthy material sprinkled with gibbsite, whole and broken pseudomorphs, and opaques. It is quite porous and some of the openings are filled with gibbsite. These are patches where opaque material and pseudomorphs are thick and close together, indicating collapse. In patches within this, and in quite thick concentrations elsewhere, is clear reddish clayey material. It shows faint aggregate birefringence and some tendency to orientation parallel to walls of openings. This could be clay skin, but whether silicate clay or goethite is uncertain.

24 to 26 inches: This is similar to 18- to 24-inch layer except that the structure seems more diffuse and less well organized into areas of one substance or another. It also contains the patches and channel fills of oriented clay.

26 to 31 inches: This is generally similar to preceding horizon, but somewhat less organized. Olivine pseudomorphs seem to be more abundant. They tend to be clumped in pockets with the opaques. Gibbsite grains are much less abundant than in horizons above, though there are some large pockets and vesicles filled with fine-grained gibbsite. In some places this is banded with or coated by brown claylike material. This horizon also contains the segregated areas of oriented clay. The difference in structure among the layers may be related to differences in crystallinity or texture of the original basalt.

80 to 85 inches: The structure and composition are somewhat similar to 26- to 31-inch layer. Structure is still coarser and less organized and probably retains some elements of the basalt. The red goethite pseudomorphs are very abundant and some are very large—much larger than seen elsewhere. They still occur in pockets with abundant opaques, but there is less of this segregation than above. Gibbsite is commonly scattered throughout but mostly in vesicles and channels. Some of the large vesicles seem to have two depositions of gibbsite—fine grained and clean around the margin and coarse grained and mixed with clay in the interior.

Halii Gravelly Clay Profile from Pit on Southwest Slope of Kilohana Crater

0 to 3 inches: Sections were made of peds and lumps impregnated together. Randomly arranged earthy material sprinkled with gibbsite and broken fragments of pseudomorphs. Occasional cemented concretions containing whole pseudomorphs and occasional balls of gibbsite. Many of the peds seem to have a dense skin. Many roots.

3 to 8 inches: These sections were also made from loose lumps. They consist of reddish translucent earthy material containing the red phenocryst pseudomorphs scattered through it. The only structure is a tendency to develop balls of varying density. The material appears to contain little gibbsite of visible size.

8 to 10 inches: This horizon is composed of several, at least three, kinds of materials arranged in separate zones, tongues, or patches with irregular boundaries. Portions are weathered basalt with the form and volume relations of the rock with gibbsite occupying the feldspar laths. Olivine pseudomorphs are quite widely spaced and the groundmass is densely peppered with small cubic opaques. Vesicles are filled with pure gibbsite. A second type of composition—structure is red translucent clay material with little organization except for a patchy variation in color density. This material contains phenocrysts, more densely spaced than the high-gibbsite material above, but the opaques are less densely spaced. Gibbsite is scarce in these areas. A third type is yellow, contains no phenocrysts, no opaques, some gibbsite, and has some birefringence indicating some clay which is organized. The first two materials could have weathered from two slightly different kinds of lava; the third has moved.

10 to 19 inches: Contains about the same variety of materials and structure as above horizon, but with a higher proportion of the gibbsite material with basalt structure. These are some bands or cracks or channels with reddish or reddish-yellow clayey material some of which shows a banded, involuted flow structure and aggregate birefringence indicating some movement and reprecipitation. These areas are very low in gibbsite or free from it. Elsewhere the specimen is pretty well filled with gibbsite in all available openings. In some places gibbsite lines the wall of a channel and the red clayey material fills it.

19 to 31 inches: Mostly red translucent clayey material with irregularly scattered phenocryst pseudomorphs and opaques. Within this are numerous large round and irregular channels and pores which are mostly filled with gibbsite and these have shape and distribution of vesicles in basalt. The red portions show quite a bit of structural organization with balls of varying density and birefringence indicating some arrangement of the clay-size material into a sort of reticulate structure, and in some cases skins around balls and around grains, and parallel to walls of channels. Some of this has enough organization and is thick enough to be easily called a clay skin, but much of it seems to be in isolated patches. None of the basalt structure with the laths preserved was seen. This horizon is quite soil-like.

31 to 33 inches: This is similar to 2-4-5, but has a higher proportion of the red clayey matrix and apparently even more indication of movement and reprecipitation, shown by involuted bands and patches and balls of various densities. The phenocryst pseudomorphs are present but many are broken up. Many of the vesicles are filled with a mixture of gibbsite and clay in alternating contorted bands. Pale-yellow clay in fairly well-oriented skins is present. There are a few small patches showing the original lath structure of basalt. Gibbsite concentration varies greatly; in some places it is almost absent, in others it fills most of available cavities and makes neat linings in pores and crevices.

33 to 42 inches: This resembles the two preceding samples in having a high proportion of red, clayey-appearing material and showing some evidence of disturbance and rearrangement. It contains patches, balls, and crack fills of paler-colored or yellow clay which shows some aggregate birefringence, often parallel to walls or surfaces. Fairly abundant pseudomorphs are irregularly distributed, tending to be concentrated in pockets. Gibbsite is probably more abundant than in preceding sample, occurring in vesicle and crack fills, but it is often mixed or interbanded with clay. Spots with original structure of basalt, with gibbsite-filled lath forms, are more common.

42 to 54 inches: This is quite different from the horizons above as indicated by sections available. Most of it seems to consist of quite homogeneous weathered basalt in which the original structure is well preserved. It was a denser type than some others for the pore and vesicle arrangement is different. There are some small irregular ones and a relatively few large round ones. As usual the phenocrysts are replaced by goethite but in many there are only shells with empty or clay-filled centers. There is a very high proportion of the brown clayey interstitial material which is apparently derived from augite. This may be the source of the high proportion of the reddish-brown clayey material in the horizons above. A second phase with sharp contact between it and the weathered basalt is a red translucent clayey material similar to much of what was described in the horizons above. This shows some aggregate birefringence, contains whole and broken pseudomorphs, but very little gibbsite.

54 to 66 inches: This is the red clay-low gibbsite material again. It contains the olivine ghosts and cubic opaques but no other basalt indications except a few small patches where some lath structure is suggested. There is quite a lot of organization in the clayey material; skins, patches, and pore fills of oriented clay are fairly common, but orientation birefringence is not strong or well developed. Gibbsite content is low. Crystals are generally sprinkled throughout the matrix but there are no concentrated accumulations in pores or other openings.

The data obtained from the optical studies show that the following weathering processes have occurred: (1) there is very little indication of halloysite clay in any of these samples. If halloysite was formed it has decomposed to form gibbsite with the last of the silica; (2) the feldspars have weathered in place to gibbsite; (3) olivine has decomposed and has been replaced by iron oxides; (4) the other silicate minerals have decomposed to iron oxide and amorphous alumina, and the latter has been deposited in the pores and interstitial openings as gibbsite; (5) aluminum oxide in solution or as gel has moved and reprecipitated as gibbsite, as indicated by the pore fillings; and (6) amorphous oxides of iron have moved and in some cases reprecipitated as goethite, but, elsewhere, have remained amorphous.

DISCUSSION

The object of this study was to trace the development of the Halii Gravelly Clay soil from the original rock, an ultrabasic basaltic lava, through the processes of rock weathering, and finally, the subsequent processes of soil formation under a humid, tropical climatic environment. The physiographical location of this soil group is on the slopes of volcanic flows emanating from the various vents of the Koloa flows of Eastern Kauai. The location occurs in a rainfall region of 100 to 200 inches, and under drainage conditions which permit a rapid infiltration of the rainwater and a free internal drainage; which consequently allows the rapid movement of gravitational water downward and laterally, providing conditions for rapid removal of dissolved constituents.

The parent rock of the three Halii Gravelly Clay soil profiles consists of a roughly stratified layer of porous olivine or other ultrabasic basaltic lavas, and associated pyroclastic materials. It appears probable that thin layers of *aa* and *pahoehoe* lavas are interbedded with cinders and volcanic ash. The parent rock is similar to the weathered boulder from the Wailua Game Reserve (figure 1). There is a great similarity in the chemical and mineralogical composition of the coarse fractions of the C horizons of the Halii soil profiles and the outer weathered layers of the boulder (tables 1, 4, 5, and 6, and figures 2 and 3). The softer unconsolidated materials derived from *aa* lava, cinders, and volcanic ash have produced weathering products similar to those developed in the weathering of the boulder. This would be expected, since the existing data indicate that the glassy pyroclastic materials of Hawaiian volcanoes are similar in composition to crystalline lavas. The glassy pyroclastic materials weather directly to amorphous materials.

The weathering of rocks is almost entirely by chemical processes. As a result, the original shape of the boulder is retained throughout the entire weathering process, even though all primary minerals have been completely decomposed and the dissolved materials removed.

The processes of rock weathering occurring in these formations under this climatic environment proceed in the following sequence: first, a rapid removal of bases by solution which leads to rapid collapse of the primary silicates with the release of the free oxides. The lack of bases and the rapid movement of percolating waters cause a rapid removal of the silica. The other free oxides quickly form amorphous hydrated colloidal oxides. The process of desilication is enhanced by the continuous presence of percolating water, which prevents the building up of a sufficient concentration of silica to combine with the iron and aluminum oxides. Titanium oxide will remain diffused in the system as its hydrated amorphous oxide as long as dehydrating conditions are absent.

The data obtained from the chemical, thermal, and optical studies of the rock weathering have established the following mineral weathering sequences:

Alumina: The lathlike feldspars have weathered directly to gibbsite. No evidence was found for an intermediate stage of halloysite in early weathering. Other aluminum-containing minerals decompose and release soluble aluminum hydroxides which are mobile and are subsequently precipitated in pores, cracks, and on the surfaces of peds. There is evidence, however, in the deep substratum that an intermediate alumino-silicate mineral, halloysite, is formed. The following mineral systems are proposed:

(a) $\underset{\text{ionic}}{Al^{+3}} \xrightarrow{OH} \underset{\text{amorphous}}{Al(OH)_3} \longrightarrow \underset{\text{crystalline gibbsite}}{Al(OH)_3}$

(b) Dehydrating surface conditions in presence of SiO_2:

$\underset{\text{amorphous}}{Al(OH)_3} \xrightarrow{SiO_2} \underset{\text{allophane}}{Al_2Si_2O_3(OH)_4 \cdot nH_2O} \xrightarrow{-H_2O} \underset{\text{halloysite}}{Al_2Si_2O_5(OH)_4}$

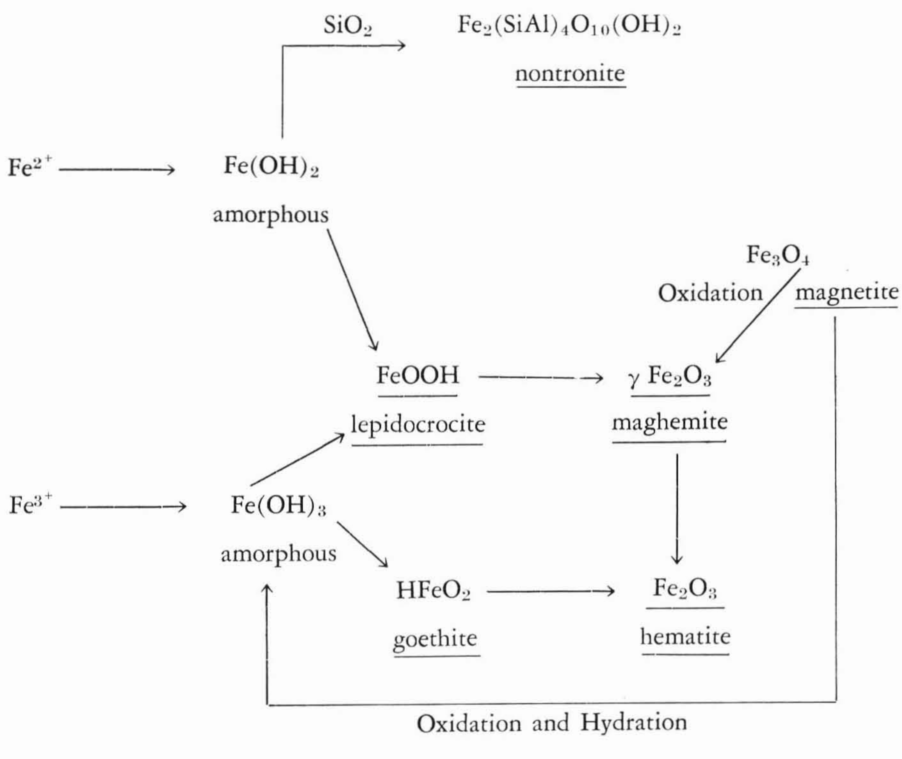
System (a) is the dominant weathering system of the primary silicates which are continuously decomposing in the rock interior in a very moist system having good drainage. The ionic and amorphous aluminum move with the drainage waters until they are converted to crystalline gibbsite. The amorphous alumina probably exists as a gel. If this is true, crystalline gibbsite probably occurs when the gel system dehydrates. Gibbsite aggregates form on exposure to drying. These aggregates form directly from colloidal clays in the manner described by Sherman (1957). If the dehydration occurs in the presence of silica, system (b) will occur, as is shown in the outer shell of the weathering boulder from the Wailua Game Refuge. There is evidence from thin sections that gibbsite may weather out of some layers and be reprecipitated in others.

There is evidence in the deep subsoils that soluble silica and amorphous alumina do react and form crystalline halloysite in pores and other rock cavities. This occurs at some depth and probably where ground waters carry a much higher silica concentration. With continued leaching and weathering, the halloysite decomposes to give system (a).

Iron oxides: The studies of the thin sections indicate that iron oxide is less mobile than the aluminum oxides, though some movement of amorphous gels does occur. This indicates that the oxidative conditions are favorable for the stabilization of ferric oxides. However, at the deeper substratums or where drainage is not as rapid, there is more evidence of iron oxide moving and precipitating in the drainage channels to form sheets in a manner similar to the aluminum oxides. Certain other features stand out in the thin sections, such as the iron oxide occurring as pseudomorphs after olivine. The magnetic properties are of interest. The weathered rock is strongly magnetic. The strong magnetism of these soils has been established to be due to maghemite, titanomaghemite, and residual magnetites (Matsusaka and Sherman, 1961; Katsura *et al.*, 1962). The low ferrous iron content, less than 4 percent of the total iron oxides, eliminates magnetite as the main source of magnetism in these weathered rocks and soils. The increase in magnetism with drying indicates the crystallization of amorphous iron oxides as possibly very poorly crystallized lepidocrocite to maghemite system of iron oxides, as predicted by Tamura and Jackson (1953). A close examination of the differential curves does indicate the possible thermal reaction for this system. Differential thermal curves developed by a more rapid heating suggest formation of maghemite. Maghemite and titanomaghemite have been identified by X-ray diffraction and other methods by Matsusaka and Sherman (1961), Katsura *et al.* (1962), and Walker *et al.* (1967). A goethite-hematite system also exists in these soils.

The existence of a ferrous iron system is also indicated by the discovery of pockets of nontronite or nontronite-like material near the weathering rock contact zone (Sherman *et al.,* 1962). Pockets, such as pores or void spaces, and protected areas under the rock were the sites at which nontronite was found. Nontronite will not persist as weathering processes proceed; it will decompose to the free oxides. Its only substantial occurrence will be in the early stages of weathering.

The following is a schematic system for the iron oxide systems revealed by the studies of rock weathering:



This system was proposed by Tamura and Jackson (1953) as the iron oxides of a rock-weathering system. The results of this study would indicate that the goethite-hematite system is not always the only iron oxide and particularly not in near-surface weathering under humid conditions where amorphous materials are involved.

Rock weathering has produced a parent material, for soil formation, which is a ferruginous bauxite. The parent material would be classified as a low- to fair-grade bauxite deposit. The weathered parent material has developed a high degree of well-organized crystallinity in iron oxide, gibbsite, ferruginous gibbsite, and nontronite, in the form of aggregates, nodules, concretions, and sheets. The fine material—less than 2 mm.—has more amorphous mineral forms, some of which readily acquire a higher order of crystallinity on dehydration on exposure. This weathered material retains the original structure of the original lava materials. Their structural forms have a marked influence on the subsequent soil-forming processes.

Soil formation has involved the following processes:

(1) The vegetation has provided for the accumulation of some organic matter in the surface horizons. A large part of the addition has been the concentration of roots in the surface horizon. The lack of penetration of roots has produced a shallow unconsolidated surface horizon which lies over weathered rocks retaining their original form.

(2) There has been some addition of silica by the vegetation cycle. There has been resilication of the amorphous aluminum oxide to allophane, especially the A_1 and B_{21} horizons. *Melastoma* has been identified as an aluminum-accumulating plant by Moomaw *et al.* (1959). Grasses are able to accumulate fairly high concentrations of silica. The decomposing organic matter thus releases both silica and aluminum to the surface. In the soil profile the vegetation cycle probably accounts for the higher silica in the surface horizon and for the formation of allophane by resilication of aluminous oxides.

(3) Extensive mineral nodulation has occurred in the soil horizons. Most notable, there has been a development of high-concentration iron oxide nodules in the form of concretions, hard mineral aggregates, and sheets in the A_1 and B_{21} horizons. Also, gibbsite forms aggregates due to local movement and to development of stable crystalline forms from the amorphous aluminum oxides. The size and number of mineral aggregates increase near the surface due to the slightly drier conditions, which apparently favor their development. There is some development of lenses and sheets.

LITERATURE CITED

ALEXANDER, L. T., S. B. HENDRICKS, and G. T. FAUST.
1942. OCCURRENCE OF GIBBSITE IN SOME SOIL-FORMING MATERIALS. Soil Sci. Soc. Amer. Proc. 6: 52–57.

CHENERY, E. M.
1948. THIOGLYCOLLIC ACID AS AN INHIBITOR FOR IRON IN THE COLORIMETRIC DETERMINATION OF ALUMINUM BY MEANS OF "ALUMINON." Analyst 73: 501-502.

CLINE, M. G., *et al.*
1955. SOIL SURVEY OF THE TERRITORY OF HAWAII. U. S. Dept. Agr. Soil Survey Series 1939, No. 25. 644 pp.

JACKSON, M. L.
1958. SOIL CHEMICAL ANALYSIS. Prentice-Hall, Inc., Englewood Cliffs, New Jersey. 498 pp.

KATSURA, T., I. KUSHIRO, S. AKIMOTO, J. L. WALKER, and G. DONALD SHERMAN.
1962. TITANOMAGNETITE AND TITANOMAGHEMITE IN A HAWAIIAN SOIL. Jour. Sed. Petrology 32(2): 299–308.

MATSUSAKA, Y., and G. DONALD SHERMAN.
1961. MAGNETISM OF IRON OXIDE IN HAWAIIAN SOILS. Soil Sci. 91(4): 239–245.

MOOMAW, J. C., M. NAKAMURA, and G. DONALD SHERMAN.
1959. ALUMINUM IN SOME HAWAIIAN PLANTS. Pacific Sci. 13: 335–341.

NORTON, F. H.
1939. CRITICAL STUDY OF THE DIFFERENTIAL THERMAL METHOD FOR THE IDENTIFICATION OF THE CLAY MINERALS. Jour. Amer. Ceramic Soc. 22: 54–63.

PIPER, C. S.
1944. SOIL AND PLANT ANALYSIS. Interscience Publishing Co., Inc., New York. 368 pp.

SHERMAN, G. DONALD.
1957. FORMATION OF GIBBSITE AGGREGATES IN LATOSOLS DEVELOPED ON VOLCANIC ASH. Science 125: 1243–1244.

———, H. IKAWA, G. UEHARA, and E. OKAZAKI.
1962. TYPES OF OCCURRENCE OF NONTRONITE AND NONTRONITE-LIKE MINERALS IN SOILS. Pacific Sci. 16: 57–62.

TAMURA, T., and M. L. JACKSON.
1953. STRUCTURAL AND ENERGY RELATIONSHIPS IN FORMATION OF IRON AND ALUMINUM OXIDE, HYDROXIDES, AND SILICATES. Science 117: 381–383.

WALKER, J. L., G. DONALD SHERMAN, and T. KATSURA.
1967. THE IDENTIFICATION OF IRON AND TITANIUM MINERALS IN TITANIFEROUS FERRUGINOUS LATOSOLS OF HAWAII. Soil Sci. Soc. Amer. Proc. (In Press.)

WRIGHT, C. HAROLD.
1939. SOIL ANALYSIS. A HANDBOOK OF PHYSICAL AND CHEMICAL METHODS. Second ed. Thomas Murby and Co., London. 276 pp.

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